PB84-194711

Microorganism Removal for Small Water Systems

SMC Martin, Inc., Valley Forge, PA

Prepared for

Environmental Protection Agency, Washington, DC

Jun 83

U.S. Department of Commerce
National Technical Information Service
NTIS

United States
Environmental Protection
Agency

Office of
Drinking Water (WH-550)
Washington, DC 20460

EPA 570/9-83-012
June 1983

PB84-194711

EPA

Microorganism Removal for Small Water Systems

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SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA 570/9-83-012	**2.**	**3. RECIPIENT'S ACCESSION NO.** PB84 194711
4. TITLE AND SUBTITLE Microorganism Removal for Small Water Systems		**5. REPORT DATE** June 1983
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) SMC Martin, Inc.		**8. PERFORMING ORGANIZATION REPORT NO.**
9. PERFORMING ORGANIZATION NAME AND ADDRESS SMC Martin Inc. 900 West Valley Forge Road Valley Forge, PA 19482		**10. PROGRAM ELEMENT NO.**
		11. CONTRACT/GRANT NO. 68-01-6285
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Office of Drinking Water (WH-550) 401 M Street SW Washington, DC 20460		**13. TYPE OF REPORT AND PERIOD COVERED** Technical
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This document is designed primarily for use by owners and operators of small water systems, those producing 500,000 gallons per day or less and serving less than 5,000 persons. Other expected users are municipal managers and consulting engineers retained by utilities. Its primary purpose is to assist personnel of small water systems to understand the importance of microorganism control and to explain the design concepts, cost estimating techniques, and operational considerations associated with current technological approaches for maintaining such control.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
microorganisms drinking water small water systems public water systems		

18. DISTRIBUTION STATEMENT Open	**19. SECURITY CLASS** *(This Report)* Non-sensitive	**21. NO. OF PAGES** 167
	20. SECURITY CLASS *(This page)*	**22. PRICE**

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

MICROORGANISM REMOVAL FOR SMALL WATER SYSTEMS

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Contract No. 68-01-6285

June 1983

ACKNOWLEDGEMENT

This manual was prepared for U.S. Environmental Protection Agency under Contract No. 68-01-6285. Mr. Chester Pauls, EPA Project Officer, provided valuable guidance to the project. The manual was compiled by SMC Martin Inc. in cooperation with the following:

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The authors are particularly grateful to Prof. Harold W. Wolf, of Texas A&M University, College Station, Texas, for his significant assistance in developing and reviewing sections of this document dealing with waterborne diseases, health and safety aspects of disinfectants, and disinfection using chlorine and chloramines.

In addition, thanks are due to Craig A. Reynolds of Aqua Media Corporation for his significant assistance in sections of this report dealing with disinfection using ultraviolet radiation.

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I. SUMMARY AND OVERVIEW

This section provides a summary of all the information which follows in the remaining chapters. The document itself is divided into eight sections plus appendices. It traces pertinent subjects from microorganism control in sources of raw water supply, through treatment control technologies, cost estimating techniques, and proper operation and maintenance procedures for each control technique discussed. It concludes with a series of short case histories representing "success stories" of the control technologies discussed herein for small water systems.

PURPOSE

This document is designed primarily for use by owners and operators of small water systems, those producing 500,000 gallons per day or less and serving less than 5,000 persons. Other expected users are municipal managers and consulting engineers retained by utilities. Its primary purpose is to assist personnel of small water systems to understand the importance of microorganism control and to explain the design concepts, cost estimating techniques, and operational considerations associated with current technological approaches for maintaining such control.

There are many small water systems that each year exceed the bacteriological Maximum Contaminant Level (MCL) contained in the National Interim Primary Drinking Water Regulations (NIPDWR). Recognizing this as a critical problem, the Environmental Protection Agency has sponsored the development of this document to explain:

1) why microorganism control is important;
2) theories of microorganism control;
3) process options for microorganism control;
4) design procedures for microorganism control;
5) process control methods;
6) operation and maintenance procedures;
7) methods of estimating costs for control processes.

This document discussing microorganism control is one of a series of five such documents being developed by EPA. The other four deal with turbidity removal, radionuclide removal, nitrate removal, and regionalization of small water supply systems.

SOURCES AND SIGNIFICANCE OF WATERBORNE DISEASE

Waterborne diseases can result when humans come into contact with waters which contain harmful microbial organisms called pathogens. These organisms may overcome the natural defenses of the body and cause disease. Prior to the introduction of chlorine as a water disinfectant in this country in 1908 and its subsequent widespread use in the U.S. and other countries, waterborne diseases such as cholera and typhoid fever were prevalent. Other ailments and infectious diseases also can result from consumption of contaminated drinking waters. The most common of these are gastroenteritis, dysentery, and infectious hepatitis. Whereas these infections are less likely to be fatal for the general public than are typhoid fever or cholera, they can cause prolonged illness and severe discomfort to the individuals infected, and death among sensitive individuals, such as infants, the already infirm, and the elderly.

The fact that each of these diseases can be transmitted by drinking water is well known. Typically, the disease-causing organisms -- various types of bacteria, viruses, and cysts -- enter the water as a result of unsanitary practices. The most common causes of contamination are from human and animal waste deposits in the watershed, leaking sewers or septic tanks, cross-connections with other sources of water, and back-siphonage resulting from negative pressure in the water distribution system.

As a way of illustrating the widespread nature and significance of waterborne diseases, consider that in 1980 more than 580 small water supply systems were persistent violators (were in violation more than four months during the year) of the national bacteriological MCL, and another 5,400 were intermittent violators (were in violation less than four months during the year). During the period 1946-1970, there were 53 outbreaks of waterborne infectious disease due to typhoid, but there were 297 outbreaks attributed to other bacterial or viral agents; these numbers probably represent only the "tip of the iceberg", however, since sporadic, random cases of gastroenteritis generally go unreported (1). A General Accounting Office report on drinking water (2) notes that the incidence of waterborne diseases has increased since the early 1950's. "From 1961 through 1978 drinking water caused 407 outbreaks of disease or poisoning resulting in 101,243 recorded illnesses and at least 22 deaths", the GAO report states.

METHODS OF REDUCING RISKS OF OCCURRENCE OF WATERBORNE DISEASES

Some organisms which cause disease in man originate with the fecal discharges of infected individuals. Since it is not practical to monitor and control the activities of human disease carriers, it is necessary to exercise precautions against contamination of a normally safe water source, to institute treatment methods which will produce a safe water, and to insure protection of the treated water during storage and distribution from becoming recontaminated (3).

Protection of the water source is the first line of defense against microbial pollution. In protecting a water source, whether it be a ground or surface source, the importance of conducting periodic sanitary surveys cannot be overemphasized. Such sanitary surveys consist of thorough investigations of the essential elements which are a part of or can impact on a water supply.

Water distribution systems also may be potential sources of bacterial contamination. The three most common ways for bacteria or viruses to enter the distribution network are through treated water which has not been adequately disinfected, by cross-connections, or by broken or leaking water lines. Other points of potential contamination are back-siphonage and openings or defects in storage reservoirs which allow entrance of small animals, such as rodents, snakes, birds, or insects.

Source protection, conducting sanitary surveys, protection of storage reservoirs, working to eliminate cross-connections and back-siphonage, and prompt repair of broken or leaking water lines all help to prevent contamination and reduce risks of waterborne diseases. Pretreatment techniques to remove suspended particulate matter (turbidity) from the raw water and disinfection to kill living microbes are necessary to reduce risks to a minimum, however.

NON-TREATMENT ALTERNATIVES

Installment of a complete treatment process to solve a microorganism problem may not always be economically feasible. If this is the case, two non-treatment alternatives should be investigated. The first is to try to find a new water source. This might be difficult and expensive for larger water supply systems, but may be quite feasible for small systems which have groundwater sources. The problem may be solved by locating wells in an area removed from the source of contamination (e.g., leaking sewer line or adjacent sanitary landfill).

The second alternative is to consider joining a regional system. Regionalization is a concept which has been successful in several states, particularly in Pennsylvania, Washington, Texas, and Alabama. The concept is one of sharing resources in order for the smaller water supply system to be able to afford highly skilled personnel on a part-time basis and thereby reduce operating and management costs. Regionalization does not necessarily mean loss of decision-making authority for a municipality, as has been implied in the past. The subject of regionalization is discussed in detail in a companion EPA document entitled, Regionalization for Small Water Systems.

TREATMENT METHODS

The "conventional" water treatment process employed widely in the United States consists of chemical coagulation, settling or clarification, filtration, and disinfection. The basic objective of the first three unit processes is to remove solid or colloidal particles from the raw water. Detailed discussions of filtration and other treatment processes can be found in a companion EPA treatment document entitled, Turbidity Removal for Small Water Systems. The most important fact for the reader to retain is that the effectiveness of the disinfection process increases with the efficiency of the turbidity removal processes. Microorganisms can become attached to the surfaces of turbidity-causing solid particles (adsorbed), or be enveloped by these particles, thereby being protected from contact with the disinfecting agent. Thus, the disinfection process may not produce a finished water of acceptable quality unless the turbidity-causing contaminants are removed from the water.

It also should be appreciated that costs to disinfect turbid waters are higher than costs to treat clear waters. This is because the chlorine or other disinfectant employed can react with the organic and other materials contained in the solid particles. Thus, instead of attacking only the microorganisms, some quantity of the disinfectant will be consumed in extraneous reactions which have no relationship to disinfection.

Disinfection

Once the turbidity-causing suspended matter has been removed, the treated water can be disinfected efficiently. Disinfection can be defined as the removal or inactivation of infectious microorganisms.

As a result of its relatively low cost and other desirable properties, chlorine currently is the most commonly used disinfectant. However, chlorine reacts with certain organic constituents of raw water supplies (humic and fulvic acids, for example) to produce halogenated compounds which impart undesirable tastes and odors (chlorophenols, for example) to the treated water. Also, trihalomethanes (THMs) may be formed as a result of chlorination. Because THMs currently are of public health concern and are regulated at a level of 0.10 mg/L MCL (4) for large water supply systems, there is considerable interest in the use of so-called "alternative disinfectants". None of these have as many desirable properties as does chlorine; therefore the use of each should be assessed by each water supply system in terms of:

- need to modify the pre- and/or post-disinfection processes;
- ability of alternative disinfectant/modified treatment process to meet all required standards;
- costs.

Disinfectants other than chlorine or hypochlorites, currently in use include

- chlorine dioxide,
- chloramines,
- ozone, and
- ultraviolet light.

The number of water treatment facilities using these alternative disinfectants is small when compared to the number using chlorine. However, each disinfectant has grown in popularity in recent years, and their use can be expected to continue to increase as more data demonstrating their advantages and disadvantages are developed. A detailed discussion of the chemistry, theory of use, and methods of application of each disinfectant is included in Section 3, DISINFECTION. Methods for estimating the costs associated with each of these disinfectants are provided in Section 5, COST ESTIMATING TECHNIQUES AND FUNDING SOURCES, and Appendix A.

NATIONAL INTERIM PRIMARY DRINKING WATER REGULATIONS (NIPDWR)

The NIPDWR were promulgated by the Environmental Protection Agency in 1975 as part of the Safe Drinking Water Act, and became effective in June 1977 (5). Maximum Contaminant Levels (MCLs) are provided for five general categories of impurities found in raw water supplies. To date, more than 20 MCLs have been established, one of which deals with bacteriological contaminants. Another deals with trihalomethanes.

Water suppliers are required by the NIPDWR to collect a minimum number of water samples each month (depending on system size) and have them analyzed for bacteriological contamination by a state or EPA-approved laboratory. The regulations also define the steps which suppliers must take in the event that test results indicate contamination. These steps include retesting and State and possibly public notification.

DISINFECTANT COSTS

Total costs for the installation and use of disinfection systems are a function of capital costs, operation and maintenance costs, and chemical costs. Chapter 5 discusses these costs and provides a method to estimate total disinfectant costs.

Of the disinfectants discussed in this document, chlorine currently is the least expensive, especially in terms of capital equipment costs. Chlorination systems also are less expensive to operate than are systems involving chloramines and chlorine dioxide. This is because these latter two disinfectants, generated on-site as required, involve the reaction of chlorine with additional chemicals, ammonia and sodium chlorite, respectively.

Generally speaking, chlorine dioxide generating systems are about twice as expensive to purchase and install as are chlorination or chloramination systems. Generation of chlorine dioxide requires the reaction of sodium chlorite solution with hypochlorite solution or gaseous chlorine. Formation of chloramines requires simple addition of either gaseous ammonia or a solution of ammonium sulfate to process waters containing hypochlorite. Alternatively, hypochlorite solution can be added to process water containing ammonia or ammonium sulfate. Thus, the primary cost difference between chlorination and chlorine dioxide or chloramination systems is the cost of additional chemicals.

Ozone currently is the most expensive of the four chemical disinfectants in terms of initial capital equipment costs, which amount to four to six times those of gaseous chlorination systems. However, once installed, ozone generation equipment operates solely by means of electrical energy. Chemical costs are nil and operating labor costs can be very low, especially if a high degree of instrumentation is installed.

Ultraviolet radiation also is generated on-site without chemicals, requires electrical energy only and little operating labor and maintenance (cleaning of the UV lamps). The life of UV generating bulbs is about one year, after which their efficiency decreases and new bulbs must be installed. Installing a new bulb is roughly equivalent to changing a light bulb in terms of effort.

Table 1 shows various comparative relationships between the disinfectants discussed in this report.

FUNDING SOURCES

Federal Sources

Federal funding programs for support of local water systems are few, the most prominent being

TABLE 1
COMPARISON OF WATER DISINFECTANTS*

Disinfectant	How Purchased	Equipment Required	Capital Cost	Chemical Cost	Operating Cost	Bacterial Disinfection Efficiency
chlorine (Cl_2)	compressed gas - 100% available Cl_2	to lower pressure and add to water	low	low	low	high
sodium hypochlorite (NaOCl)	aqueous solution - 5-15% available Cl_2	to meter solution	low	low	low	high
calcium hypochlorite [$Ca(OCl)_2$]	solid	to prepare and meter solution	low	low	low	high
chloramine	prepared on-site in product water	a) to lower pressure and add ammonia to water; or b) to meter aqua NH_3; c) to prepare and meter ammonium sulfate solution	low	low	low	lowest
chlorine dioxide (ClO_2)	generated on-site in solution	ClO_2 generator system	low-medium	medium	low	second highest
ozone (O_3)	generated on-site in air	air preparation, ozone generator, contactor and off-gas destructor	high	nil	low (power)	highest
ultra-violet light	generated on-site	UV generating system	medium	nil	low (power)	high

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* These comparisons generally are based on bacterial disinfecting capability, and are not generally applicable to cysts, such as Giardia lamblia.

the Farmers Home Administration (FmHA) combination grant/loan program for financing of small, rural water and sewer systems. The total program funding level in fiscal year 1982 (October 1, 1981-September 30, 1982) was about $400 million. Most of this money is made available through state FmHA offices in the form of long-term, low interest loans. Typical financial terms in the past consisted of 40-year loan periods at 5 to 7 percent interest rates.

Little federal assistance other than the FmHA program is expected in the foreseeable future.

State Sources

As many as 17 states have some type of funding program for water systems and there is an increasing trend developing in this area. In 1981, the voters of both Pennsylvania and New Jersey approved sizeable state bond issues for water supply improvements. The State of Washington's program to assist water systems has been on-going since 1972. Other states are expected to develop funding mechanisms for small water supply systems in the near future.

OPERATION AND MAINTENANCE (O&M)

None of the systems discussed in this document will operate continuously without some regular and planned attention from a water treatment plant operator. Therefore, the prudent water supplier will require the disinfection system vendor to provide start-up assistance and training, and to provide detailed O&M manuals for the equipment. A schedule of preventive maintenance activities for the equipment should be developed and plant operators should be required to follow it. Section 6 contains a discussion of desirable operation and maintenance procedures.

HEALTH AND SAFETY ASPECTS OF DISINFECTANTS

Since disinfectants used in potable water systems also are strong chemical oxidants, operators must learn to handle these toxic and potentially injurious substances properly. Safety training and emphasis on precautionary plant operating measures to ensure personnel safety are of extreme importance. Of the chlorination chemicals discussed, sodium and calcium hypochlorites generally are the safest to use because they are purchased in liquid and solid forms, respectively.

Gaseous chlorine was used as a chemical warfare agent during World War I. Short exposure to gaseous vapors of chlorine can cause injury or even death. Emphasis on correct methods of changing chlorine cylinders, ensuring proper ventilation and a separate room for handling chlorine which has provisions for rapid access to the outdoors, and having safety equipment such as gas masks readily available are of utmost importance.

Sodium chlorite, the chemical from which chlorine dioxide is generated, is incendiary in its pure, dry state. Thus, any spills of chlorite solutions should be cleaned up quickly, but never with paper or rags, which after contacting the wet chlorite can become combustible after the water has evaporated.

Once generated, chlorine dioxide should remain in aqueous solution and not be allowed to escape into the air, where it can present an explosion hazard.

Ammonium sulfate is a harmless powder which exhibits no unusual hazards, such as toxicity, fire or explosion. Liquid ammonia is supplied in cylinders under pressure from which the gaseous material is volatilized. Gaseous ammonia is a choking gas, ingestion of which can cause temporary upsets to human digestive systems. Precautions should be taken to avoid breathing either ammonia or chlorine vapors.

Ultraviolet radiation can be very damaging to the skin and especially damaging to human eyes. This fact is recognized by UV systems suppliers, who normally design their systems so that it is not possible to see any light emanating from the unit during its operation. Since the UV portion of the spectrum is invisible, care should be taken to avoid looking into UV generating units unless the power is turned off. Light generated by UV systems during operation is similar in effect, although not as intense, as that given off during arc welding of metals.

Ozone is a very powerful oxidizing agent which can cause temporary upsets to human digestive systems in low concentrations, but can be fatal at high concentration. On the other hand, commercially available ozone generating systems are safe to operate since the operator never has to come into contact with the chemical. If a leak of ozone is detected, simply shutting off the electrical power to the generator will halt the production of ozone. An instrument to monitor the level of ozone in ambient air in the room housing the ozone generation and/or contacting equipment can be installed. Exposure to as little as 0.3 to 0.4 ppm concentrations of ozone in air can cause light-headedness and nausea. However, recovery from short term exposures to ozone, even for periods up to an hour, to date has not been reported to be other than complete.

II. INTRODUCTION

This section discusses sources and kinds of waterborne diseases, the National Interim Primary Drinking Water Regulations, and the requirements for sampling and monitoring, types of microbiological analysis, record keeping and reporting of results, and the concept of disinfectant residuals.

SOURCES OF WATERBORNE DISEASES

Waterborne illness may occur when water containing a sufficient concentration of harmful microbial organisms (called pathogens) is consumed or otherwise contacted intimately. The pathogens of concern may be one or more species of bacteria, viruses, protozoa, or even other forms such as fungi, rickettsia, or helminths. Typically, they enter a raw water supply as a result of wastewater discharges, waste deposits, or leaking sewers or septic tanks. Sometimes they may even enter a finished water distribution system via a connection with a contaminated source or system (cross-connection) which subsequently allows reversal of flow (back-siphonage).

Water supplies should be obtained from the best water source available. It may be a surface or a groundwater source or even a combination of the two. The source water should be consistently adequate in quality and quantity. Quality characteristics might be especially critical during periods of unusual stress, such as during heavy rainfall runoff, extensive drought, or upstream spills. Wastewater discharges into sources of drinking water must comply with all local, state, and federal regulations. This includes appropriate disinfection for contaminated or potentially contaminated discharges. Most outbreaks of waterborne illness occur when using untreated or inadequately treated groundwater supplies. Popular myths about the purity and safety of groundwaters tend to lull users into a false sense of security. Although the various states have different regulations concerning water treatment and disinfection, the strategy recommended by water supply professionals is to disinfect all groundwater supplies and to clarify, filter, and disinfect all surface water supplies and groundwater supplies containing excessive turbidity.

KINDS OF WATERBORNE DISEASE

Present day control strategies for the prevention of waterborne disease historically are linked to the control of typhoid fever, which is caused by a bacterium. However, it is now known that organisms such as cysts and viruses are active agents in waterborne disease outbreaks. Both treatment and monitoring techniques must be designed to accommodate these differences successfully.

Even in a contaminated raw water source, the causative agent, such as the typhoid organism, would be extremely difficult to locate among the myriad of other organisms that would be present. Hence, an easily found substitute (called a 'surrogate') was developed to indicate the likely presence of disease-causing organisms. The coliform group of organisms, which are common inhabitants of the intestinal tracts of mammals (warm blooded animals) was chosen. This surrogate approach is based on the theory that if coliform organisms are present at a high enough concentration, then some intestinal pathogen also might be present, and therefore the bacterial quality of the water is questionable.

The surrogate approach has been highly successful in helping overcome the scourge of waterborne typhoid fever. As waterborne typhoid fever gradually came under control over the years, it was observed that the incidence of other illness also decreased (1). This occurred because many other disease-causing intestinal microbial agents are destroyed during the disinfection process, in spite of the fact that some are more resistant to disinfection methods than is the coliform indicator organism, when pure strains of organisms are tested.

Table II shows some common waterborne illnesses and the agents that cause them (6). The organism most commonly implicated in recent documented waterborne outbreaks is Giardia, an organism of which very few people are even aware. Giardiasis is usually a relatively mild illness causing cramps, diarrhea, and the typical distress of intestinal upset. However, in some individuals it is a very severe, debilitating disease.

Other diseases also can be waterborne under unusual circumstances. For example, tuberculosis has occurred in children who fell into a sewage-contaminated canal (7). Nosocomial infections (hospital infections) have occurred because Pseudomonas aeruginosa developed in hospital water systems (8). A few strains of the coliform bacterium Escherichia coli -- called 'opportunistic pathogens' -- may cause diarrhea and other diseases.

Because there is so much variability among people and organisms, there can be no "safe" level of contamination. Transmission of waterborne disease can be minimized by appropriate treatment and disinfection, protected water supply distribution systems always under adequate pressure, and a vigilant program against cross-connections.

THE NATIONAL INTERIM PRIMARY DRINKING WATER REGULATIONS (NIPDWR)

When Congress enacted the Safe Drinking Water Act in 1974, it included as one of five major provisions the development of primary regulations for the protection of public health. As part of Section 1412 of the Act directing it to develop such regulations, EPA promulgated the National Interim Primary Drinking Water Regulations (5) in 1975, which became effective on June 24, 1977. The NIPDWR established maximum contaminant levels (MCLs) for several general categories of contaminants commonly found in raw water supplies. A maximum contaminant level is defined as "the maximum permissible level of a contaminant in water which is delivered to the free flowing outlet of the ultimate user of a public water system". The only exception to this definition is

TABLE II

WATERBORNE ILLNESSES AND CAUSATIVE AGENTS (6)

Illness	Agent
Typhoid fever	*Salmonella typhi*, (bacterium)
Paratyphoid fever	*Salmonella paratyphi*, (bacterium)
Bacillary dysentery	*Shigella* spp., (bacterium)
Cholera	*Vibrio cholerae*, (bacterium)
Amoebic dysentery	*Endamoeba histolytica*, (protozoan)
Infectious hepatitis (Hepatitus A)	Hepatitis A Agent (virus)
Giardiasis	*Giardia lamblia*, (protozoan)
Gastroenteritis	Rotavirus, Norwalk Agent (viruses) *Campylobacter jejuni*, *Yersinia enterocoliticus* (bacteria), as well as other bacteria and viruses

that turbidity levels are measured at the point of entry to the distribution system as opposed to the extremities.

As part of the implementation strategy for the regulations, each state and territory has been given the option of accepting primary enforcement responsibility (primacy) for the regulations. As of mid-1982, more than 50 of the 57 states and territories had assumed primacy. In those few states which have not assumed primacy, EPA operates the program and enforces the regulations.

The NIPDWR sets limits on the kinds and amounts of contamination allowed in drinking water, defines monitoring and reporting requirements, and requires systems that do not meet the regulatory requirements to publicly notify users. MCLs have been established for more than 20 selected organic chemicals, inorganic chemicals, turbidity, microbiological and radiological contaminants. These contaminants were selected because their presence in concentrations above their respective MCLs are known, or are strongly suspected, to cause adverse effects on human health.

Each contaminant has specific monitoring and reporting requirements. By law, all water systems are responsible for collection of finished water samples, for having them tested by an EPA or state approved testing laboratory, and for having copies of the results sent to the appropriate state or federal agency.

The NIPDWR makes a distinction between the monitoring and reporting requirements applicable to community and non-community systems. A community system is defined as one having at least 15 service connections used by year-round residents or regularly serving at least 25 year-round residents. Mobile home parks, small residential areas, and apartment communities fall into this category. A non-community system has at least 15 service connections used by travelers or intermittent users at least 60 days per year, or serves an average of at least 25 individuals at least 60 days per year. Water supplies for campgrounds, some restaurants, motels, factories, service stations, and schools fall into this category.

Community water systems must monitor and report levels of all contaminants listed in the NIPDWR. For coliforms, community systems must test monthly; however the State may reduce the sampling frequency, based on a sanitary survey of a system that serves less than 1,000 persons from a groundwater source, except that in no case shall it be reduced to less than once per quarter.

Non-community public water systems must monitor and report levels of nitrate, turbidity (where surface waters are used) and microbial contaminants. Coliform analyses must be conducted quarterly, but this frequency may be modified by the State based on the results of sanitary surveys. For the non-community systems, the remaining contaminants must be monitored and reported at intervals specified by the State. Generally, states require reporting on a timely basis, depending upon the contaminant.

THE MAXIMUM CONTAMINANT LEVEL (MCL) FOR BACTERIOLOGICAL CONTAMINANTS

In reviewing this discussion of the bacteriological MCL, the reader should be aware that individual states may have regulatory requirements in addition to those of the NIPDWR.

The NIPDWR allows approved laboratories to analyze bacteriological samples using one of two methods, either the membrane filter technique or the multiple tube fermentation method, and MCLs have been established for both methods. The multiple tube fermentation method allows either 10 mL or 100 mL sample portions to be used in the coliform multiple tube fermentation test. The regulations establish requirements both for single samples and for the average arithmetic mean of all samples tested each month regardless of which method is used. The requirements when using each method of analysis are summarized below:

MCL Using the Membrane Filter Method

- For all systems, the number of coliform bacteria shall not exceed one colony per 100 mL as the arithmetic mean of all samples examined per month.
- For systems which collect and examine less than 20 samples per month, the coliform level must not exceed four colonies per 100 mL sample in more than one sample per month.
- For systems that collect and examine more than 20 samples

per month, the coliform level must not exceed four colonies per 100 ml in more than five percent of the samples.

MCL Using the Multiple Tube Fermentation Method (10 mL sample portions)

- For all systems, coliforms must not be present in more than 10 percent of the total tubes per month.
- For systems which examine fewer than 20 samples per month, coliform bacteria shall not be present in three or more portions in more than one sample, or
- For systems that examine more than 20 samples per month, coliform bacteria shall not be present in three or more portions in more than five percent of the samples.

MCL Using the Multiple Tube Fermentation Method (100 mL sample portion)

- For all systems, coliforms must not be present in more than 60% of total tubes in any month.
- For systems that examine less than five samples per month, coliforms shall not be present in more than one sample, as indicated by gas in all five tubes.
- For systems that examine five or more samples per month, coliforms shall not be present in more than 20% of the samples, as indicated by gas in all five tubes.

For community and non-community systems that are required to sample at a rate of less than four per month, compliance shall be based upon sampling during a 3-month period, except that, at the discretion of the State, compliance may be based upon sampling during a one-month period.

Significant Facts For the Small System Owner/Operator

The wording of the bacteriological MCL is very complex. Since most small systems are expected to retain an outside certified laboratory to collect and analyze the samples, attempts to understand all the complex language may appear to be superfluous. However, it is the owner of the system who is responsible for ensuring compliance with the law. Therefore, some degree of understanding is necessary to insure that:

1) the proper number of samples is collected;

2) the meaning of test results is comprehended; and

3) correct results are reported to appropriate state and/or federal offices.

NIPDWR MANDATED COLIFORM SAMPLING AND REPORTING FOR SMALL SYSTEMS

The minimum number of routine monthly coliform samples currently required by the NIPDWR is given in Table III. The number of samples required is based upon the population served. Although the table shows that no less than one sample is required each month, it is possible for small supplies serving 25 to 1,000 people,

TABLE III

BACTERIOLOGICAL SAMPLES REQUIRED PER SERVED POPULATION

Served Population	Minimum Routine Monthly Samples
25 - 1000	1
1001 - 2500	2
2501 - 3300	3
3301 - 4100	4
4101 - 4900	5
4901 - 5800	6
5801 - 6700	7

which use groundwater, and having a history of little or no coliform contamination, to obtain their state's approval to sample and report only quarterly. Two types of reports are required by the NIPDWR:

1) suppliers must report the results of routine bacteriological analyses to the state on a timely basis;

2) if the MCL is exceeded and confirmed by a follow-up check sample, suppliers must notify both the state and the water consumers.

The public notification requirements for community and non-community systems differ significantly. See Reference 5 for a detailed discussion of these requirements.

A positive coliform sample is not a matter to be taken lightly -- it is a basis for genuine concern. Good sanitary engineering practices dictate a series of successive steps to determine the seriousness of the problem. In addition, the NIPDWR requires the following minimum procedures:

1) when the number of coliforms exceeds four per 100 mL, when using the membrane filter procedure, at least two consecutive daily check samples shall be collected and examined from the same sampling point. Additional check samples shall be taken daily until the results from at least two consecutive check samples show less than one coliform per 100 mL;

2) when coliforms occur in three or more 10-mL portions of a single sample, when using the multiple tube procedure, the same procedure as above shall be followed until the check samples show no positive tubes;

3) when coliforms occur in all five of the 100-mL portions of a single sample, at least two daily check samples shall be collected plus additional check samples daily until two consecutive

samples show no positive tubes.

If the check samples persist in being positive, a process of more intensive sampling and system checking must begin if it has not already been initiated.

Some states allow water systems to reduce the number of bacteriological samples normally required by up to 75%, provided that certain other conditions are met:

1) the system must undergo a sanitary survey;

2) chlorine residual samples are to be taken at points representative of the distribution system at a frequency of at least four per substituted coliform sample;

3) chlorine residuals are determined at least daily;

4) no less than 0.2 mg of free residual chlorine* per liter of water shall be maintained throughout the distribution system;

5) when a free chlorine residual of less than 0.2 mg/L is found, the chlorine residual of the water must be retested at the same point within the hour;

6) if the resampling shows a residual of less than 0.2 mg/L, the state shall be notified and a sample for coliform analysis must be collected at that same point, also within the hour. These results must be reported to the state in a timely manner.

Figures 1 and 2 summarize the current reporting procedures for single samples and arithmetic mean values for samples analyzed monthly, respectively, by the membrane filter method. Figures 3 and 4 summarize the current reporting procedures for the corresponding samples analyzed by the multiple tube fermentation method (10 mL). Figure 5 summarizes the current reporting procedures for chlorine residuals (9) when a water supply system elects to substitute chlorine residual monitoring for bacteriological monitoring.

RECORDKEEPING REQUIREMENTS FOR RESULTS OF MICROBIOLOGICAL ANALYSES

Good recordkeeping is the cornerstone of effective long-term operation of quality drinking water supplies. Records provide historical bases from which to interpret current data and help prevent recurring problems. Records provide a basis for answering information requests from the public, and may prove invaluable in the event of legal action.

It is the responsibility of every water supplier to keep adequate records and to ensure that the reporting requirements of the primary drinking water regulations are met. Results of bacteriological

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* After the chlorine demand of a water has been satisfied, the amount of chlorine which can be measured in solution is called 'free residual chlorine'. This concept will be discussed later in this Section.

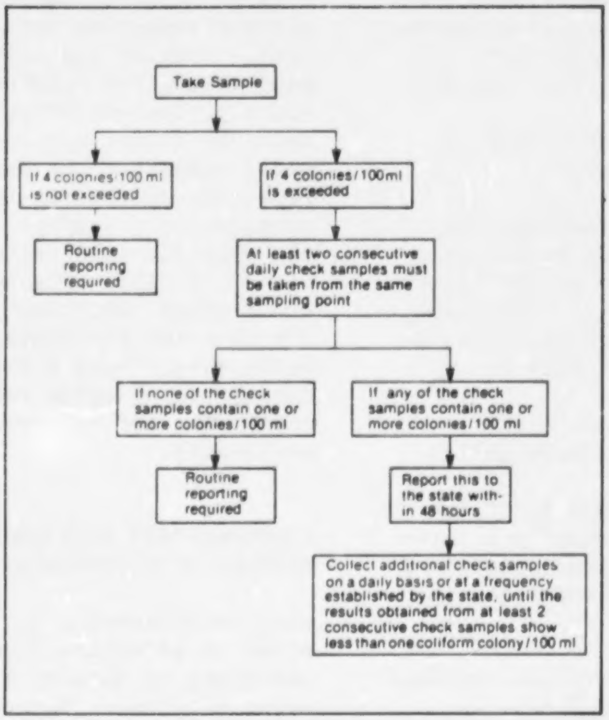
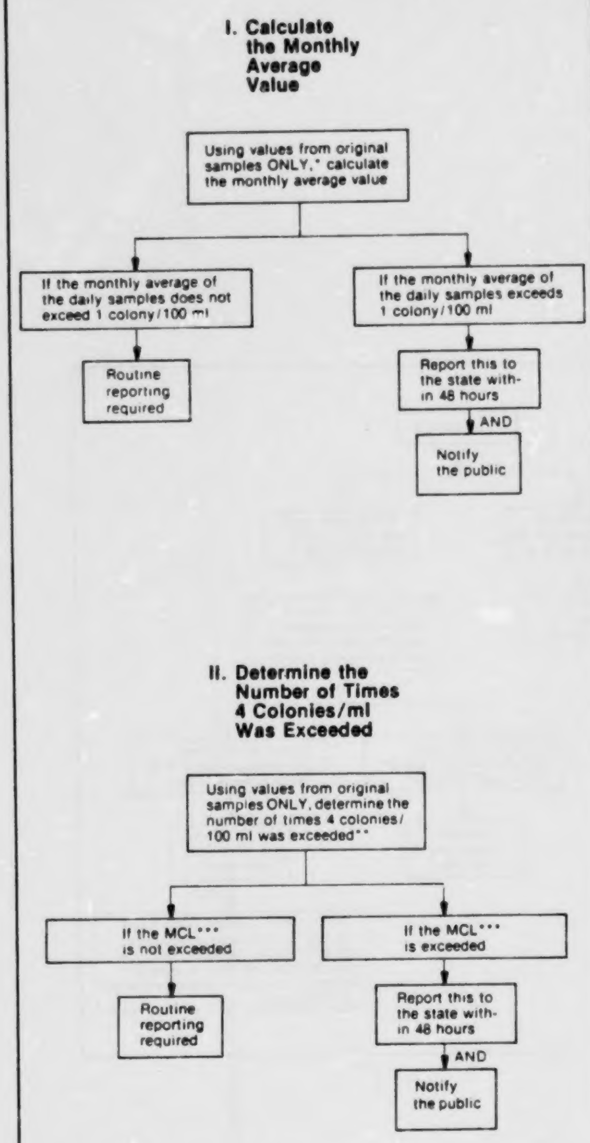

Take Sample
If 4 colonies/100 ml is not exceeded
If 4 colonies/100ml is exceeded
Routine reporting required
At least two consecutive daily check samples must be taken from the same sampling point
If none of the check samples contain one or more colonies/100 ml
If any of the check samples contain one or more colonies/100 ml
Routine reporting required
Report this to the state within 48 hours
Collect additional check samples on a daily basis or at a frequency established by the state, until the results obtained from at least 2 consecutive check samples show less than one coliform colony/100 ml

Figure 1. Reporting Procedures - Microbiological Contaminants - Membrane Filter (7) for Single Samples


I. Calculate the Monthly Average Value
Using values from original samples ONLY,* calculate the monthly average value
If the monthly average of the daily samples does not exceed 1 colony/100 ml
If the monthly average of the daily samples exceeds 1 colony/100 ml
Routine reporting required
Report this to the state within 48 hours
AND
Notify the public
II. Determine the Number of Times 4 Colonies/ml Was Exceeded
Using values from original samples ONLY, determine the number of times 4 colonies/100 ml was exceeded**
If the MCL*** is not exceeded
If the MCL*** is exceeded
Routine reporting required
Report this to the state within 48 hours
AND
Notify the public

*Check sample values are not to be used when calculating the monthly average. (Refer to the membrane filter recordkeeping form shown in Appendix 4.)

For systems taking **fewer than 20 samples per month, merely count the number of samples exceeding 4 colonies/100 ml.

For systems taking **20 or more samples per month,** calculate the percentage of samples exceeding 4 colonies/100 ml. (Refer to the membrane filter recordkeeping form shown in Appendix 4.)

***The MCL states that coliform presence shall not exceed 4 colonies/100 ml in more than one sample if fewer than 20 samples collected per month or 4 colonies/100 ml in more than 5% of the samples if 20 or more are examined per month. Refer to the multiple-tube recordkeeping form shown in Appendix 4.

Figure 2. Reporting Procedures - When Calculating Monthly Membrane Filter Results (7)

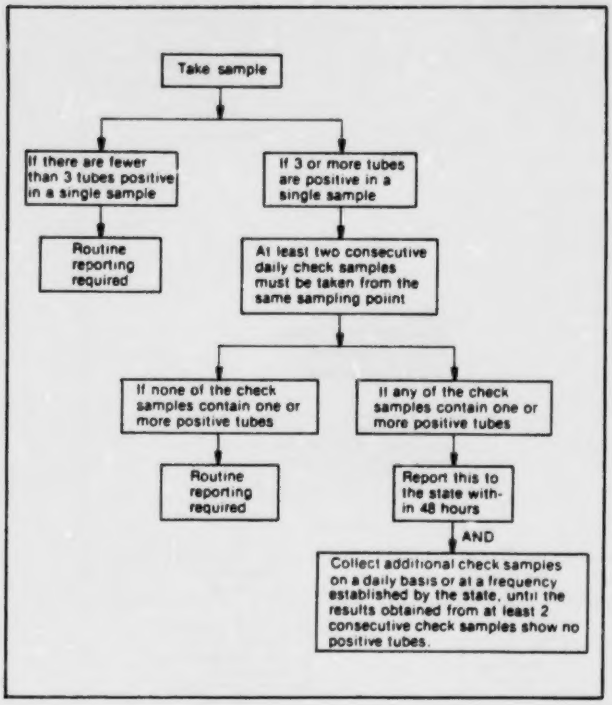
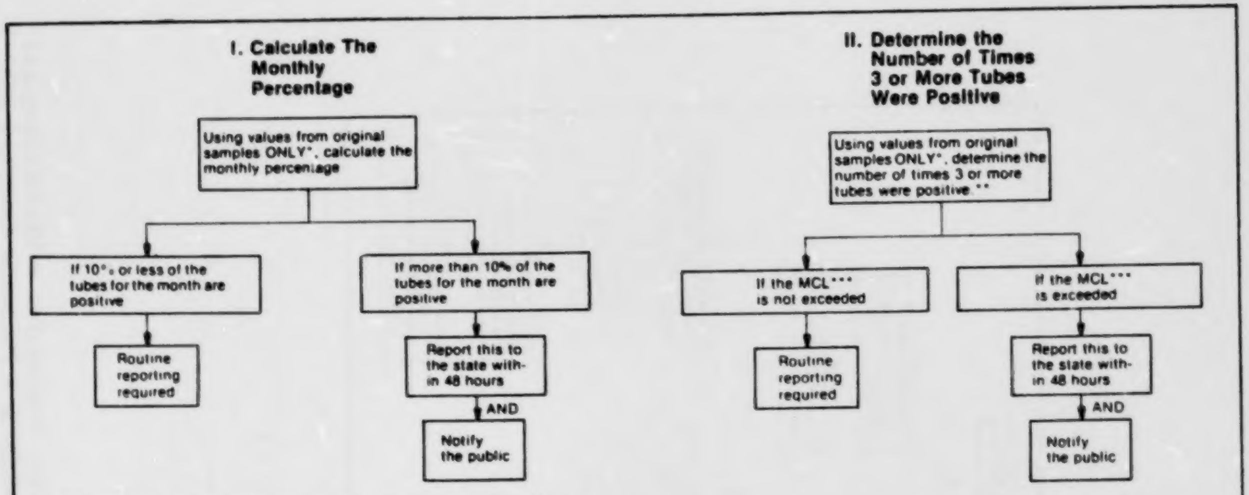

Take sample
If there are fewer than 3 tubes positive in a single sample
If 3 or more tubes are positive in a single sample
Routine reporting required
At least two consecutive daily check samples must be taken from the same sampling point
If none of the check samples contain one or more positive tubes
If any of the check samples contain one or more positive tubes
Routine reporting required
Report this to the state within 48 hours
AND
Collect additional check samples on a daily basis or at a frequency established by the state, until the results obtained from at least 2 consecutive check samples show no positive tubes.

Figure 3. Reporting Procedures - Microbiological Contaminants - Multiple-Tube Fermentation Method (10 mL) (7)


I. Calculate The Monthly Percentage
Using values from original samples ONLY*, calculate the monthly percentage
If 10% or less of the tubes for the month are positive
Routine reporting required
If more than 10% of the tubes for the month are positive
Report this to the state within 48 hours
AND
Notify the public
II. Determine the Number of Times 3 or More Tubes Were Positive
Using values from original samples ONLY*, determine the number of times 3 or more tubes were positive.**
If the MCL*** is not exceeded
Routine reporting required
If the MCL*** is exceeded
Report this to the state within 48 hours
AND
Notify the public

*Check sample values are not to be used where calculating the monthly percentages. (Refer to the multiple tube recordkeeping form shown in Appendix 4.)

For systems taking **fewer than 20 samples per month, merely count the number of samples which contained 3 or more positive portions.

For systems taking **20 or more samples per month**, calculate the percentage of samples containing 3 or more positive portions.

***The MCL states that not more than 1 sample may have 3 or more portions positive when fewer than 20 samples are examined per month OR not more than 5 [illegible] of the samples may have 3 or more portions positive when 20 or more samples are examined per month.

Figure 4. Reporting Procedures - When Calculating Monthly Multiple-Tube Fermentation (10 mL) Results (7)

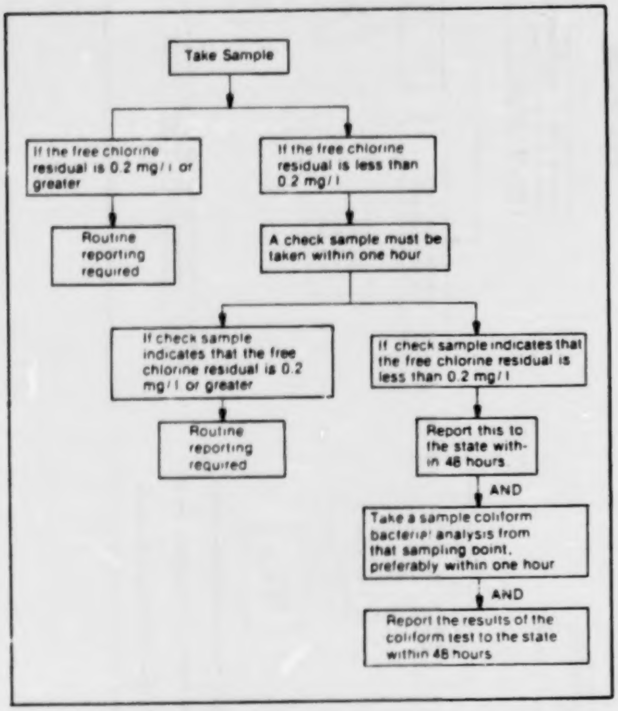

Take Sample
If the free chlorine residual is 0.2 mg/l or greater
If the free chlorine residual is less than 0.2 mg/l
Routine reporting required
A check sample must be taken within one hour
If check sample indicates that the free chlorine residual is 0.2 mg/l or greater
If check sample indicates that the free chlorine residual is less than 0.2 mg/l
Routine reporting required
Report this to the state within 48 hours
AND
Take a sample coliform bacterial analysis from that sampling point, preferably within one hour
AND
Report the results of the coliform test to the state within 48 hours

Figure 5. Reporting Procedures - Microbiological Contaminants - Chlorine Residual (7)

tests must be retained for at least five years. The following information must be collected to meet minimum requirements:

1) date, place, time of sampling;
2) name of person who collected the samples;
3) sample disinfectant concentration, whether it is routine or a check, raw or treated water, etc.;
4) date and place (laboratory) of analysis, test method used, results, and person who performed the analysis.

A supplier may develop his own form for this purpose or use the standard forms included in Reference 5 and reproduced in Appendix B.

SIGNIFICANCE/IMPLICATIONS OF THE PRESENCE OF COLIFORMS AND DISINFECTANT RESIDUALS

There are two important indicators of bacteriological safety in drinking water systems:

- presence or absence of coliforms;
- concentration of disinfecting agent.

Presence Or Absence Of Coliforms

As stated previously, the coliform organism normally is present in the intestinal tract of all mammals. Hence, whenever coliforms are found to be present in drinking water, the assumption can be made that the possibility of intestinal pathogens being present also exists. The absence of coliforms, however, does not guarantee that pathogens are absent. The finding of any coliforms in a finished drinking water sample requires an immediate response from the operator to ensure that a more significant problem does not exist. Therefore, to assure good quality of the water, plant operating personnel must be capable of obtaining routine and check samples, reviewing treatment facility operations, and checking distribution system integrity.

A related matter of primary importance is to determine if the coliforms found actually were present in the water system sampled, or if they gained entry to the sample via some pathway of contamination unrelated to the quality of the drinking water. A possible source of bad samples is a customer's faucet, either an inside or outside tap, in which coliforms have become established in the faucet gasket material or aerator. For this reason, proper sampling technique is essential.

The NIPDWR requires sampling at the tap, except for turbidity, which should be measured at the point of entry of treated water into the distribution system. For operational control, however, the sampling locations chosen for monitoring coliforms and disinfectant residuals should include a point where the water leaves the treatment plant and enters the distribution system and another point in the distribution system at the greatest distance from the treatment plant. "The greatest distance" usually implies that the water also takes the longest time to reach that point. It is best to make calculations to ensure this is true, because it is important to sample the "longest flow" points. The samples withdrawn at these most distant points must meet the criteria for coliforms and/or disinfectant residuals.

The prudent operator will use the bacteriological sampling program to help develop data that provide a background of information for the entire distribution system through a pattern of representative samplings.

Concentration Of Disinfectant Residual

Drinking water supplies are disinfected for one principal reason: to kill or inactivate pathogens. The disinfection process occurs mainly in the treatment plant where concentrations, contact times, and other conditions are controlled so that bacterial and other waterborne pathogens are dramatically reduced. This does not mean that the treated water is sterile; it is not. However, sufficient disinfecting chemical usually is added, not only to eliminate pathogens, but also to help control the possible growth of other microorganisms which may be present.

If the treated water enters a distribution system and there is no residual disinfectant remaining in the water, those surviving organisms that find a suitable living environment in pipeline sediment, crevices at pipe joints, or packing materials, may grow and reproduce. This situation can result in undesirable consequences, such as slimes breaking loose and entering the consumer's drinking water, foul tastes and odors, and increased corrosion and pipeline deterioration. Providing a residual of disinfecting agent throughout the distribution system minimizes the possibility of such events.

BACTERIOLOGICAL ANALYSIS

Bacteriological analyses are performed by State or EPA approved private laboratories or by State operated laboratories, depending upon the preference of the State. Many state health department laboratories do not charge for routine bacteriological analyses of public water supply system samples. Commercial, State, or EPA-certified labs charge from $5 to $25 per sample, plus the costs of sample transportation. Results are reported in one of two ways, depending on the analytical method used. If the membrane filter test is used, the results will be expressed as coliform colonies per 100 mL of sample. If the multiple tube fermentation method is used, the results will be reported as a most probable number (MPN) of coliform organisms (per 100 mL) of sample or in terms of the number of tubes positive.

Membrane Filter

The bacteria in a measured sample are filtered onto the surface of a thin membrane which is transferred to a culture dish containing nutrients for coliforms to grow and then placed in a 35°C incubator. Any coliforms present will grow into visually observable differentiated colonies which -- if of the appropriate type -- are counted. Each colony is presumed to come from a single viable bacterium in the sample.

Multiple Tube Fermentation

Each of five sterile culture tubes containing a suitable lactose or lauryl tryptose broth and an inverted tube (to demonstrate gas production) are inoculated with 10 mL of the water sample. These are placed in an incubator (35°C). Any coliforms will grow, and in growing will produce gas which is trapped in the inverted tube. Thus, a visual observation of gas in the tubes is an indication of coliform presence. If only one tube has gas and the other four do not, it can be presumed that the sample of water used to inoculate the tubes (50 mL) contained at least one coliform (or 2 per 100 mL). Since it is possible that two coliforms could have been in that one tube but not in the other four, a statistical correction is applied and called a most probable number (MPN).

Table IV shows the relationships between the Most Probable Number Index per 100 mL determined by the multiple tube fermentation method (using five 10-mL samples) and the 95% confidence limits to be applied. For example, if three tubes are found to give positive reactions, the MPN index per 100 mL is 9.2, and one can be 95% confident that the true MPN falls between 1.6 as the lower limit and 29.4 as the upper limit.

For the most part, routine testing using these methods will indicate whether the drinking water supply is reasonably safe from waterborne illnesses. It does not, however, provide positive proof of a safe system, nor is it all that a responsible operator should be concerned about. Continuing efforts must be directed at maintaining pressure, eliminating and insuring against cross-connections, keeping the system tight, maintaining an adequate level of residual disinfectant, being alert for changes in water quality, keeping the chemical/physical systems operating to remove contaminants, maintaining adequate supplies of chemicals, maintaining proper records, and monitoring the water source itself.

DISINFECTANT RESIDUAL ANALYSIS

The current primary drinking water regulations specify one method for analyzing chlorine residual in finished drinking water. This is the DPD colorimetric method which is described in detail in Reference 10.

Analytical methods for measuring residuals of other disinfectants are not yet specified in the primary drinking water regulations. The primary reason for this is the current lack of sufficient experience in the United States with other disinfectants and their analyses. Various methods exist for determining chlorine dioxide and ozone, and each method is characterized by problems of interference by other oxidants, difficulties in attaining accurate measurements, or complexities in the procedures themselves.

Methods for analyzing residuals of each disinfectant -- chlorine, chlorine dioxide and ozone -- are described below. Methods for analyzing ultraviolet residuals are not discussed because ultraviolet radiation does not leave a residual; this is one of its shortcomings. Chloramine residuals

TABLE IV

MPN INDEX AND 95% CONFIDENCE LIMITS FOR VARIOUS COMBINATIONS OF POSITIVE AND NEGATIVE RESULTS WHEN FIVE 10-mL PORTIONS ARE USED (10)

No. of tubes giving positive reactions out of five of 10-mL each	MPN Index/100 mL	95% Confidence Limits	
		Lower	Upper
0	<2.2	0	6.0
1	2.2	0.1	12.6
2	5.1	0.5	19.2
3	9.2	1.6	29.4
4	16.	3.3	52.9
5	>16.	8.0	infinite

can be determined by using the DPD method, as can chlorine dioxide.

It is not important that the reader understand fully the procedures or chemistries of the analytical methods discussed. However, it is extremely important to have knowledge of the limitations of analytical procedures and to know which methods can be relied upon. Only through this knowledge can the owner/operator be assured that a disinfectant residual is being maintained and customers protected.

Chlorine

Chlorine residual tests must be conducted immediately after sampling, since agitation or exposure to sunlight will cause the chlorine residual to disappear rapidly. Tests can be carried out at the sampling location using a portable field test kit which uses the DPD colorimetric method. This is the only chlorine residual test procedure currently approved for use in connection with compliance monitoring under the primary drinking water regulations. It is a simple method based on color comparisons that can be carried out in about five minutes.

Several suppliers of chlorine residual test kits are listed in Table V.

Analysis of residual chlorine is based on the instantaneous reaction of free available chlorine with the DPD indicator to produce a red color. The depth of this color can be converted into a free chlorine value using a visible light spectrophotometer

TABLE V

SOME SUPPLIERS OF CHLORINE RESIDUAL TEST KITS

Capitol Controls Co., Advance Lane, Box 211, Colmar, PA 18915

Chemply, Division of United Chemicals, Inc., Box 18049, Pittsburgh,
PA 15236

Fischer & Porter Co., Environmental Division, County Line Rd.,
Warminster, PA 18974

Hach Co., Box 389, Loveland, CO 80537 (Branch Offices in
Santa Clara, CA; Orlando, FL; Tucker, GA; Palatine, IL;
Ames, IA; Lake Charles, LA; Cherry Hill, NJ; Chapel Hill,
NC; Cleveland, OH; Houston, TX; and Olympia, WA.

Wallace & Tiernan, Div. of Pennwalt Corp., 25 Main St.,
Belleville, NJ 07109

as provided in a standard field kit.

Chloramines also can be determined using the DPD method by adding a second reagent (potassium iodide) after taking an initial photometer reading. After adding a small amount of potassium iodide, another reading is taken to measure chloramines.

Chlorine Dioxide

Although several methods are specific for pure solutions of chlorine dioxide, in actual practice chlorine dioxide typically is generated in the presence of free residual chlorine. In addition, small concentrations of chlorite ions (the starting material) and chlorate ions (resulting from the disproportionation (simultaneous oxidation and reduction) of chlorine dioxide will be present.

The DPD procedure is not selective for chlorine dioxide alone; it will measure the total concentration of all the above oxidants which may be present. When chlorine dioxide is generated in the presence of significant quantities of free residual chlorine, addition of ammonia will destroy the free residual chlorine, leaving chloramines, chlorine dioxide, and chlorite and chlorate ions, the sum total of which can be determined upon addition of DPD and conducting the analysis in the same manner as for free residual chlorine.

Standard Methods (10) contains descriptions of four other analytical methods, each of which has specific advantages and disadvantages. These methods, all of which will also measure total oxidants in addition to ClO_2, are:

- iodometric;

- orthotolidine-oxalic acid;
- amperometric titration with phenyl arsine oxide;
- DPD-ferrous ammonium sulfate.

In order to determine chlorine dioxide selectively and accurately currently requires a complex sequence of analyses, which would place a great analytical burden on small water supply systems. On the other hand, EPA currently recommends a maximum dosage of 1 mg/L of chlorine dioxide for use in water treatment (11). If this recommendation is followed, there will be no necessity to determine specific chlorine dioxide residuals. Instead, the DPD (or other) method can be used to measure and control total residual oxidants in the treated water. If chlorine dioxide is the only oxidant added, and at a maximum dosage of 1 mg/L, then the concentration of total residual oxidants will not exceed 1 mg/L.

Ozone

In solution, dissolved ozone is very reactive and, except in triple-distilled water near its freezing point, quickly decomposes into oxygen from which it is generated. Therefore, when ozone is utilized as a terminal disinfectant, it produces a short-lived residual which disappears in a matter of minutes in the storage tank. However, ozone can be used as the primary disinfectant, with the ozonized water being treated with chlorine, chlorine dioxide, or chloramine later in the process to produce a residual.

During ozonation for disinfection, however, dissolved residual ozone is sufficiently stable so that its concentration can be analyzed accurately, provided the analysis is conducted quickly on samples taken in or close to the contact chamber. In fact, many European and Canadian water supply systems which utilize ozonation for disinfection, control the amount of ozone added by monitoring the dissolved residual obtained after the initial ozone demand of the process water has been satisfied.

Two primary methods for measuring residual ozone in water are applicable to small water systems. These are:

- iodometric (wet chemical, manual)
- amperometric (instrumental, manual or automatic)

Iodometric Procedure

To a sample of water containing ozone, a solution of starch and potassium iodide is added. Dissolved ozone is destroyed while oxidizing iodide ion to free iodine which, in turn, forms a deep blue-colored complex with the starch. This is titrated to colorless with standardized sodium thiosulfate solution, and the amount of dissolved ozone is calculated from the quantity of thiosulfate required. This is the cheapest method, but requires manual chemical analysis.

Amperometric Procedure

This method requires purchase of an in-line instrument which continuously samples the water and monitors total oxidant concentrations colorimetrically. Several current suppliers of amperometers (which also can be used to measure free and combined chlorine residuals and chlorine dioxide) are Fischer & Porter, Wallace & Tiernan, Infilco-Degremont, Hach Co., and Ionics, Inc. The basic principles of operation of the first three of these instruments are described by Paré (12).

The choice between use of the manual iodometric method and the automatic amperometric titration method involves consideration of cost and available skills. If a trained laboratory technician is on staff, the manual iodometric method is sufficient. However, if trained personnel are not available, the automatic analyzer should be purchased along with the ozone system. If a small water system is financially able to purchase an ozonation system, it should seriously consider purchase of an automatic residual ozone monitor.

III. ASSURING SAFE, PATHOGEN-FREE DRINKING WATER

Providing the public with a safe, pathogen-free drinking water is the shared responsibility of system designers, owners, and operators. Public health officials assist by providing professional advice and technical guidance based on local experience. Ensuring quality potable product water begins with the protection of source waters and includes programs and efforts designed to maintain that protection throughout its treatment, transportation, and use. The other factors involved in supplying safe drinking water are diagrammed in Figure 6. They include a quality system which is well operated and maintained, and properly staffed, and capable of complying with the National Interim Primary Drinking Water Regulations.

Source waters can be either surface or groundwater, or a combination of the two. The majority of small public water supplies utilize groundwaters, and groundwater protection has received increasing emphasis in recent years as society has learned to appreciate its value.

This section presents summary discussions of non-treatment and treatment alternatives. Detailed discussions of system designs for specific disinfectants, and operation and maintenance are the subjects of Sections 4 and 6, respectively.

NON-TREATMENT ALTERNATIVES

Watershed Management

In general, the better the quality of the raw water supply (source waters), the easier and cheaper it is to treat and the better will be the final product quality. Protecting the source of a drinking water supply is the first step to quality water. For example:

- Uncontrolled development leads to erosion, paving over of groundwater recharge areas, and more polluted runoff. Runoff from roadways carries oils, trash, and sediment. Erosion from disturbed, developing areas increases turbidity which requires more expensive treatment processes. Watershed protection starts with land use planning and control of development.

- Dumping (whether intentional or accidental) of inadequately treated, potentially toxic solid and liquid wastes onto the land or into water may lead to serious, sometimes irreversible pollution of the watershed and source waters. Accidents with the potential for damage and outright violations should be reported promptly to the authorities that have jurisdiction.

- Poorly constructed septic tank systems and collector sewers often are identified with fecal contamination of groundwaters and water systems. This problem can be especially severe in limestone areas and wherever fissured rocks permit the unrestricted movement of underground water. Local and state health officials need public help for effective

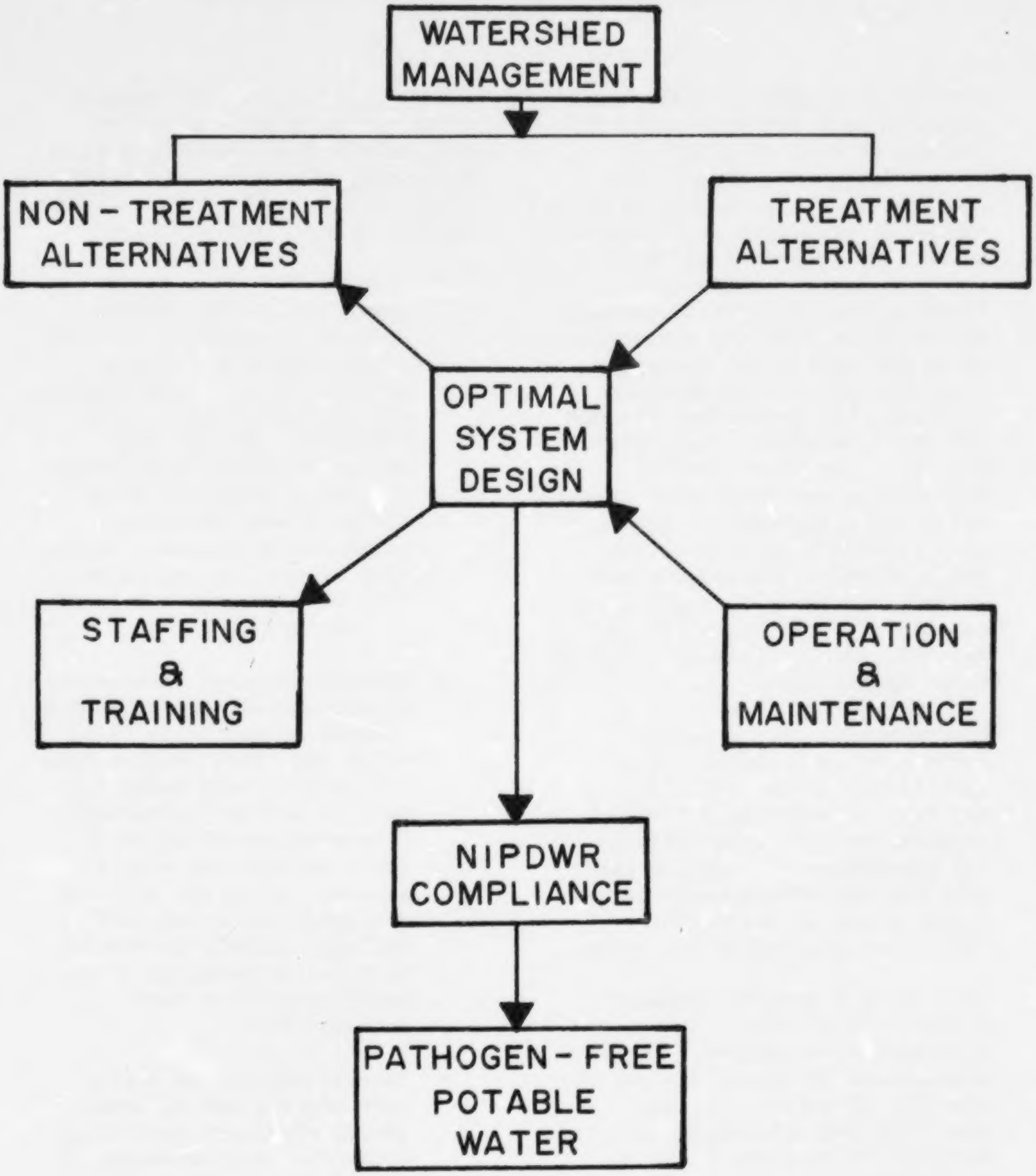

WATERSHED MANAGEMENT
NON - TREATMENT ALTERNATIVES
TREATMENT ALTERNATIVES
OPTIMAL SYSTEM DESIGN
STAFFING & TRAINING
OPERATION & MAINTENANCE
NIPDWR COMPLIANCE
PATHOGEN - FREE POTABLE WATER

Figure 6. Factors Contributing to Assuring Safe, Pathogen-Free Drinking Water

septic tank system controls and sewer maintenance programs.

- A few small communities draw their water supplies from surface sources into which contaminants have been discharged, surreptitiously, accidentally, or legally. Any surface source must be considered potentially contaminated; contaminated discharges simply render them more so. Failure to effectively treat waste discharges generally will result in increased treatment costs to subsequent users. It is every dischargers' responsibility to treat the discharges at least to the degree required by the controlling agencies whose requirements are, in turn, largely governed by the downstream uses of the water.

- Overly intensive agricultural practices can result in contaminated surface and groundwaters. Animal feedlots and runoff from heavily used pastures and also from dense populations of wildlife can contribute to fecal pollution of surface waters. Poor agricultural crop practices result in increased erosion and higher turbidity and sediment transport, which, in turn, result in filling in of reservoirs. Over-fertilization and indiscriminate use of pesticides can add potentially harmful substances to runoff waters and destroy non-target beneficial organisms and wildlife. Awareness of these and other agricultural practices is essential to appropriate watershed management.

Other Non-Treatment Alternatives

Small water systems faced with the need for upgrading or the addition of new facilities in order to provide safe drinking water should first consider the possibilities offered by other approaches herein addressed collectively as "Other Non-Treatment Alternatives". In general, these alternatives mean the obtaining of water, in whole or in part, from a different source or supply superior in quality.

Examples include:

Source Substitution

Treatment and disinfection costs are related directly to water quality. Costs often can be greatly reduced by switching from a turbid surface water to a clear well water. It can be expected that such a change will reduce costs of disinfection as well. There are many other factors that also must be considered, however, such as iron, hardness, or stability.

Blending

A high quality water source of insufficient capacity to fully replace an existing water source of lesser quality still may be used to advantage to reduce treatment needs and costs. For example, blending of waters from the higher quality source might reduce the concentrations of chlorine-demanding substances, thereby permitting better disinfection with less chlorine. Such a course of action, however, requires prudence because other water quality parameters might be affected as well -- such as stability.

Regional Systems

Regionalization is a concept which involves sharing of resources in order for each system to be able to avail itself of the services of skilled personnel, thus lowering operating and management costs. This concept has been tried in several states, and has been most successful in Pennsylvania, Washington, Texas and Alabama.

A regional system can be formed only if the concept has the support of local political bodies and the public. Several types of entities can be formed: these include formation of a special district, authority, or association, a non-profit water supply corporation or an investor-owned (profit making) water system; entering into informal agreements or setting up joint service organizations with other jurisdictions in the region; or entering into basic service contracts with private service organizations. The type of entity formed depends entirely on the particular needs of the local water systems forming the regional system.

Substantial planning is required before a regional system can become a reality. The basic steps in the planning process are to decide the following:

- benefits to be derived from the regional system;
- services and functions of the entity;
- management structure that will govern the entity;
- legal structure that will meet area needs;
- financing needs and plans for funding.

Once these basic decisions are made, the process becomes one of implementation. If most local political and institutional bodies are in agreement with the plan, the process of forming a regional entity, although time-consuming, is relatively easy. However, if some of the local institutions disagree with the concept and the plan, the regionalization process can become extremely difficult and time-consuming, often resulting in failure.

One of the primary reasons that regionalization has not been more widely practiced is the fear of loss of authority by owners of small water systems, usually municipalities. In those states in which regionalization schemes have been successful, the benefits derived usually have outweighed their costs -- both monetary and non-monetary. Other barriers may preclude formation, however. These include financial and legal difficulties and geographical dispersion.

Regionalization often has been viewed as the total physical interconnection of a number of systems. Although this is indeed its ultimate definition, other forms of regionalization are possible and are more prevalent. These include:

1) provision of laboratory services to a number of utilities by a single central laboratory;

2) provision of management and financial services by a central authority; and

3) operation and maintenance of facilities by a single set of operators.

Benefits which can be derived from regionalization are numerous:

1) Services often can be provided at lower unit costs as the quantity of water produced increases. This is often referred to as "economies of scale".

2) Pooling of skills, resources and knowledge enhances the ability to deliver services.

3) The number of poorly operated and maintained systems can be reduced.

4) The regional entity has greater capabilities to plan and design facilities, secure financing for needed capital improvements, and operate and maintain systems.

5) More highly skilled management and operations personnel can be attracted and retained.

These concepts are developed in detail in a companion EPA document entitled Regionalization for Small Water Systems.

TREATMENT ALTERNATVES

Predisinfection

Treatment methods for control of pathogens in drinking water inevitably involve some form of disinfection to inactivate the microorganisms. However, pretreatment may be required to remove substances which interfere with the disinfection process. The most common interfering substance in potable water treatment is turbidity, caused by fine particulates suspended in water. Excessive turbidity interferes with the action of disinfectants and is usually associated with the presence of many extraneous organic substances which collectively also interfere with the disinfection process. The subject of turbidity removal is addressed in a companion EPA document entitled Turbidity Removal for Small Water Systems.

DISINFECTION

Introduction

Disinfection means the destruction of disease-causing organisms. It is not the same as sterilization, which means the killing of all organisms. Disinfection of drinking water long has been measured in terms of the number of coliform organisms that remain in the water after it has been subjected to a disinfection process. Such treatment does not render the water sterile, nor is it necessarily pathogen-free because a few forms, such as the hardy cysts and spores of pathogens might survive if initially present.

However, substantial experience has demonstrated that serious waterborne illness rarely occurs when disinfection to the coliform levels specified in the NIPDWR is carried out meticulously.

This section of the document presents discussions of factors known to affect disinfection by each of the disinfectants. The chemistry of each disinfectant is discussed, along with methods for the application of each, establishment of residuals, factors affecting disinfecting efficiency of each, formation of by-products, and availability of commercial equipment.

Desirable properties for a chemical disinfectant include:

- non-toxic to humans at concentrations applied for disinfection;
- high germicidal power (kills a high proportion of microbes at low dosages);
- stability (so as to provide a residual* effect);
- solubility;
- economy;
- dependability;
- ease of use and measurement; and
- ready availability to the small water system.

Chlorine and its hypochlorite compounds satisfy all of the desirable properties of this list. The other disinfectants each lack one or more attributes.

Disinfection With Chlorine

Chlorine, symbolized chemically as Cl_2, is the disinfectant most commonly used by U.S. water utilities. It is available commercially in three forms:

Form	Formula	Name
gas	Cl_2	chlorine gas
solid	$Ca(OCl)_2$	calcium hypochlorite
aqueous solution	$NaOCl$	sodium hypochlorite

The gaseous form is used most frequently, especially by larger water utilities.

Chemistry of Chlorination

Chlorine in the gaseous form will react with water to form hydrochloric acid and hypochlorous acid:

$$\underset{\text{chlorine}}{Cl_2} + \underset{\text{water}}{H_2O} \longrightarrow \underset{\text{hydrochloric acid}}{HCl} + \underset{\text{hypochlorous acid}}{HOCl}$$

---

* The addition of disinfectant in excess of the amount required to disinfect water in the plant provides a residual quantity of that disinfectant in the treated water. The stability of that residual disinfectant will depend upon the quality of the water to which it is added. Ammonia will react with and destroy free residual chlorine; some dissolved organics will react with and destroy residuals of chlorine, chlorine dioxide, and ozone. UV radiation will not produce a disinfecting residual concentration. Residual ozone will disappear within a few hours of addition.

The hypochlorous acid then will react with the water by dissociation to an extent determined by the pH:

$$\underset{\text{hypochlorous acid}}{HOCl} \longrightarrow \underset{\text{hypochlorite ion}}{(OCl)^-} + \underset{\text{hydrogen ion}}{H^+}$$

(pH is a measure of the concentration of hydrogen ion in the water. The more hydrogen ion present, the lower is the pH value. Conversely, the lower the hydrogen ion concentration, the higher will be the pH value)

At neutral pH (pH = 7.0), almost 80% of the hypochlorous acid will remain in the highly effective HOCl form and the remainder will exist in the less-effective $(OCl)^-$ form. As the pH increases, however, an increasing amount of HOCl will react with water to form the $(OCl)^-$ form. At pH 8.0, for example, almost 80% of the hypochlorous acid will exist as the hypochlorite ion, almost a complete reversal of the situation which exists at pH 7. Hence, effective pH control is essential for good chlorine disinfection. Figure 7 shows these relationships determined at 0°C and at 20°C.

When the chlorination is conducted by adding either sodium hypochlorite or calcium hypochlorite, the chemical reactions result in an alkaline (basic) product as compared to the acidic product obtained when using the gas (as denoted in the equations above by HCl and H^+):

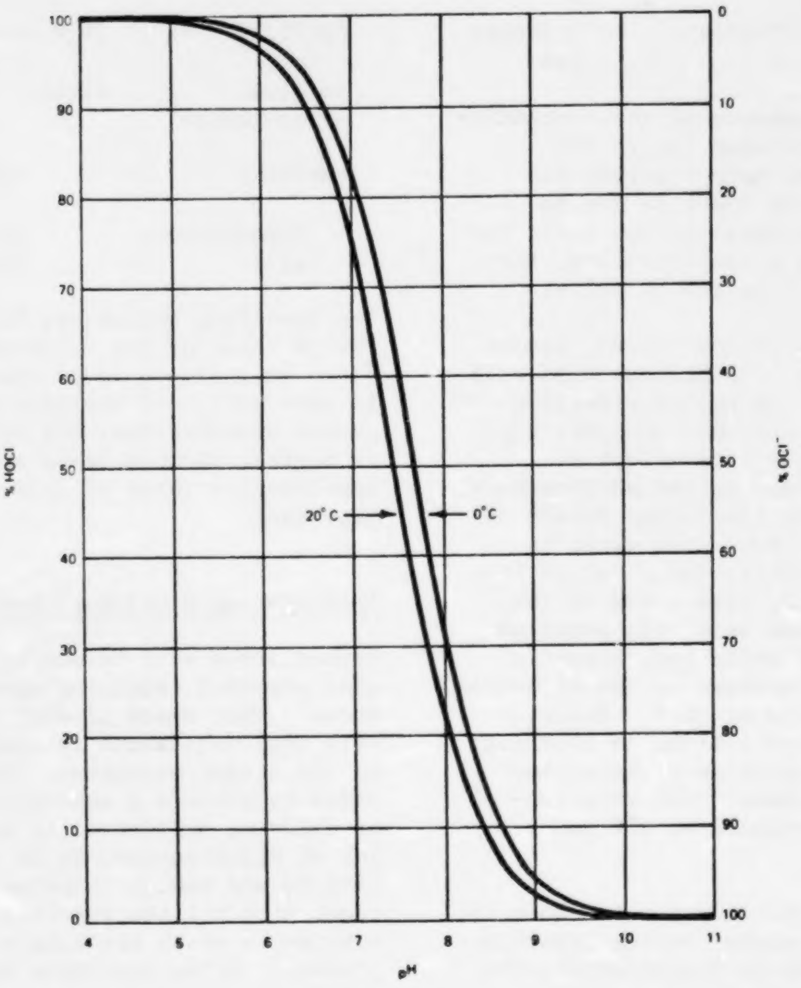
$$\underset{\text{sodium hypochlorite}}{NaOCl} + \underset{\text{water}}{H_2O} \longrightarrow \underset{\text{hypochlorous acid}}{HOCl} + \underset{\text{sodium hydroxide}}{NaOH}$$

$$\underset{\text{calcium hypochlorite}}{Ca(OCl)_2} + \underset{\text{water}}{2H_2O} \longrightarrow \underset{\text{hypochlorous acid}}{2HOCl} + \underset{\text{calcium hydroxide}}{Ca(OH)_2}$$

The resulting hydroxides increase the pH value of the solutions. Since an increase in pH results in less HOCl, and therefore poorer disinfection, the ability to control pH when using the hypochlorite forms of chlorine is important.

Establishing a Chlorine Residual

Hypochlorous acid is one of the most powerful oxidizing agents known. That means it will react with many substances in addition to the target organisms. In order to achieve a concentration of chlorine sufficient to do the job of disinfection, it is necessary to add enough chlorine to react with all the reactive substances which are likely to be present. These reactions consume chlorine and are collectively called the "chlorine demand". Thus, the chlorine demand of a water must be satisfied before an



Source: Water Chlorination Principles and Practices, AWWA No. M20, (1973), p. 12.

Figure 7. Distribution of Hypochlorous Acid and Hypochlorite Ions in Water at Different pH Values and Temperatures

adequate job of disinfection can be expected. This essential operation is tricky because the consumption of chlorine (really of hypochlorous acid) by the chlorine-demanding materials is a function of time. For a given water, it is virtually certain that the chlorine demand measured after five minutes of contact with chlorine will be greater than the chlorine demand measured after ten minutes of contact.

The concentration of chlorine determined by an analytical procedure is called the "available chlorine residual", and it means only that amount of chlorine which remains available for the disinfecting operation. The residual may be either a free available residual or a combined available residual. Free available chlorine is essentially the sum of HOCl and $(OCl)^-$ concentrations. Combined available chlorine is the sum of the concentrations of mono- and di- chloramines (see later discussion of chloramines).

Intuitively, one would expect that each mg/L of chlorine added to water would be measurable as hypochlorous acid or hypochlorite ion. This is not the case, because the chlorine reacts with many substances present in the water in a complex way.

To understand the complex reactions of chlorine better, refer to Figure 8 (13), which shows what is called typically a "breakpoint curve". The amount of chlorine added is on the horizontal scale and the amount of available chlorine determined by an analytical procedure is on the vertical scale. Assume that chlorine is added slowly and that the water contains small amounts of reduced substances such as sulfides and ferrous iron, some organic materials, and some ammonia, all of which exert a chlorine demand. The initial amount of chlorine added will be taken up by the reduced substances and the analysis for *free available chlorine* (HOCl and OCl) will show that none is present. After the chlorine demands of the reduced substances are satisfied, then the HOCl will react with ammonia and some of the organics present to yield chloramines and chloro-organic compounds.

When all of the ammonia and chlorine-demanding organics present have reacted with chlorine, the addition of more chlorine results in the HOCl oxidizing the same materials it just helped create. The strange phenomenon observed is that the addition of more chlorine results in a *decrease* in the amount of residual (at this point a *combined residual*) indicated by the analytical procedure. When this oxidation is complete (called the breakpoint), then the addition of still more chlorine results in an increase in the amount of available chlorine measured. Note that the breakpoint must be passed before a free residual can accumulate and persist.

It is important to be aware that the above illustration is considerably more complex than as described because the reactions taking place are time-dependent. For this reason, a breakpoint curve is difficult to recreate.

Factors Affecting Disinfection Efficiency of Chlorine

Chlorine in the free state (HOCl + OCl^-) is a highly effective disinfectant. Figure 9 (14)

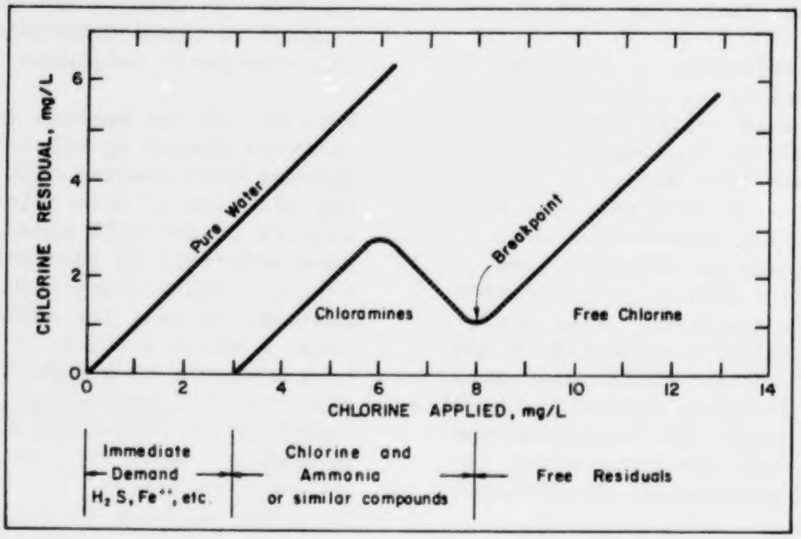


Figure 8. Graphical Representation of the Breakpoint Chlorination Reaction. The straight line at the left shows that chlorine residual is proportional to dosage in pure water. When impurities are present, they exert an initial chlorine demand (14).

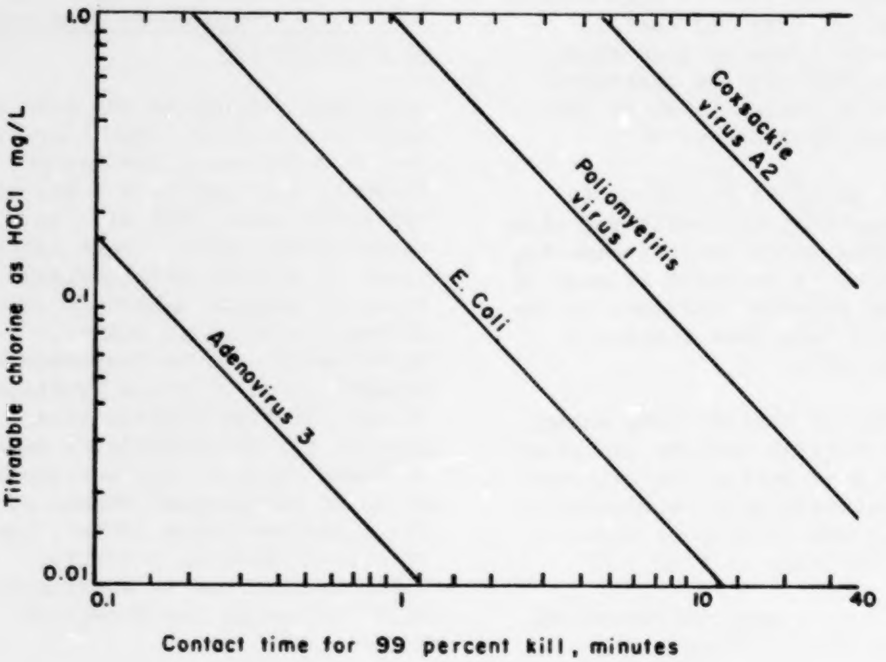


Figure 9. Concentration of Chlorine as HOCl Required for 99 Percent Kill of E. Coli and Three Enteric Viruses at 0 to 6°C. Note: mg/L = g/m^3 (15).

shows that 1 mg/L HOCl caused a 99 percent kill of the test bacteria and viruses in six minutes or less under the conditions of exposure used in this study.

Effective disinfection using chlorine requires careful attention to:

- concentration of free available chlorine -- high enough in the plant so that it never drops to less than 0.2 mg/L at the farthest (time basis) point in the distribution system;
- pH as close to 7.0 as is practical or consistent with other water quality aspects, so as to maintain as much of the chlorine residual in the HOCl form (see Figures 7 and 10);
- time of contact long enough to achieve microbe inactivation -- baffle the chlorine contactor well to eliminate the possibility of short circuiting of flow.

Other factors also influence the chlorine disinfection process. Temperature will affect the ratio of $HOCl:OCl^-$ (see Figure 7) and the disinfection rate -- this being faster at warmer temperatures. However, usually there is no means available to the operator to control temperature. Perhaps the most important factor for the operator to be aware of is that there are some organisms which are extraordinarily resistant to chlorine disinfection, and that following the rules of good practice does not guarantee their destruction. These organisms include the spores of tetanus and botulism, for example, and the cysts of protozoans such as amoeba and *Giardia*. Fortunately, these are not generally present in groundwaters, the major source of supply for small systems. Surface water supplies should be treated by coagulation and sedimentation, plus filtration, in addition to disinfection, in order to control cysts.

Potentially Harmful By-Products of Chlorination

Chlorine, whether in the form of hypochlorous acid, hypochlorite ion in solution or the gaseous element, not only is a powerful oxidizing agent, but also is a chlorinating agent. When chlorine comes in contact with certain types of organic materials (such as humic and fulvic acids), chlorinated organic compounds are formed. Some of these by-products of the chlorine disinfection process may be potentially damaging to human health. One particular group of halogenated organics, the trihalomethanes (THMs), has been identified as potential human carcinogens -- substances which encourage the growth of cancer cells.

Humic or fulvic acids are produced during the decay of vegetation. Slow moving rivers or lakes which drain heavily vegetated areas are likely to contain significant concentrations of humic and fulvic acids, which can be termed "trihalomethane precursors".

The term "trihalomethane" is used rather than "trichloromethane" because some of the compounds isolated after chlorination have been shown to contain bromine, as well as chlorine. It has been

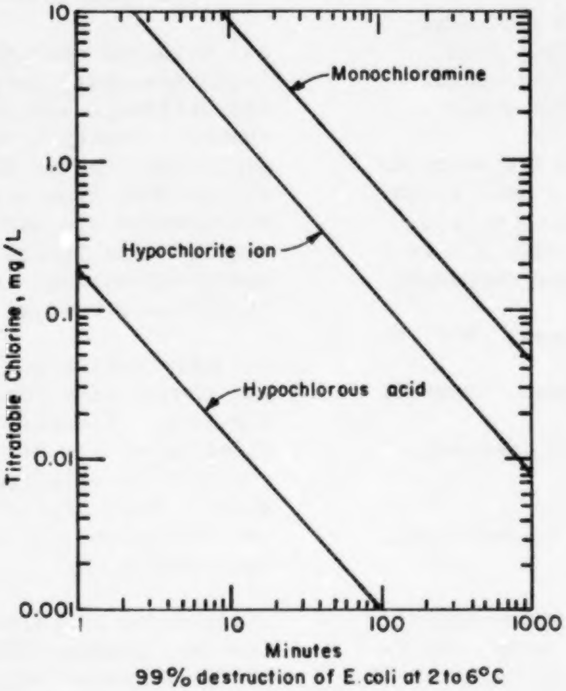


Figure 10. Comparison of the Germicidal Efficiency of Hypochlorous Acid, Hypochlorite Ion and Monochloramine for 99 Percent Destruction of E. Coli at 2 to 6°C (15).

demonstrated that when waters being chlorinated also contain bromide ions, these can be oxidized by chlorine (or hypochlorite) to an oxidation state at which the organic contaminants become brominated as well as chlorinated.

Generically, the trihalomethanes have the chemical formula:

$$\begin{array}{c} X \\ | \\ H - C - X \\ | \\ X \end{array}$$

where: H = a hydrogen atom
C = a carbon atom
X = chlorine and/or bromine atoms

There are four THMs for which an MCL of 0.10 mg/L has been established for large water supply systems. This 0.1 mg/L MCL is the total of all four compounds:

bromodichloromethane, $HCCl_2Br$

chlorodibromomethane, $HCBr_2Cl$

tribromomethane (bromoform), $HCBr_3$

trichloromethane (chloroform), $HCCl_3$.

The summation of the concentrations of these four compounds is referred to as "total trihalomethanes" (TTHMs).

Other trihalomethanes are known which contain iodine, but these are not currently regulated by the EPA.

Several techniques are known for reducing the levels of TTHMs in drinking water supplies; these can be generalized as follows:

1) reduce the level of THM precursors (organic materials which produce THMs upon chlorination) before chlorination;

2) replace chlorine with a disinfectant which does not produce THMs;

3) remove THMs after they have been formed.

4) move the point of chlorine application until after the majority of organic materials has been removed.

All evidence available to date indicates that, once formed, THMs are difficult and costly to remove. Aeration will physically strip the lighter di- and trichloro-THMs from solution, but the heavier di- and tribromo-THMs require more intensive (and energy-consuming) aeration for significant removal.

Granular Activated Carbon (GAC) can remove some THMs from water supplies. However, the useful lifetime of the GAC before reactivation is required is rather short. Both capital costs of installing GAC and regeneration costs are high.

Changing to a disinfectant which does not produce THMs appears to be the simplest solution, and the subject is discussed in detail in this chapter. However, it is generally recognized that removal of THM precursors before chlorination is the best technological (although not necessarily the most cost-effective) approach to lowering concentrations of TTHMs.

For small water supply systems, the following approaches to lowering THM precursor levels are suggested:

1) Consider alternative raw water supplies containing lower amounts of THM precursors.

2) Reevaluate the amount of chlorine currently being employed. Can the same degree of disinfection be attained with lower chlorine dosages?

3) If chlorine currently is added before pretreatment (chemical addition, coagulation, sedimentation, filtration), consider moving the point of chlorination. Rather than adding chlorine with the chemicals, consider adding it after the filtration step. If this is not practical, consider adding the chlorine just before the filter, but after chemical pretreatment.

4) Optimize the efficiency of the pretreatment steps. Remember that the function of pretreatment is to remove turbidity and dissolved organic chemicals. Can improvements be made in the way chemicals are being mixed and/or in coagulating, settling and filtering?

5) The use of a stronger oxidant (ozone, chlorine dioxide) added with chemical treatment (replacing prechlorination) is practiced for removal of tastes and odors, colors, iron and manganese, and other purposes at some water treatment plants. In such cases, these oxidants have been shown to improve the flocculation process and in some cases to lower the concentrations of THM precursors. However, in many other cases, it has been shown that ozonation, while effective in lowering turbidity levels, increases the THM formation potential.

6) The alternative disinfectants chloramine, pure chlorine dioxide, ozone or ultraviolet light do not produce THMs even in waters which contain high levels of THM precursors. Each of these disinfectants is discussed later in this section and should be considered in systems having a trihalomethane problem.

Disinfection With Chlorine Gas

Chlorine is a poisonous, yellow-green gas at ordinary temperatures and pressures. It is supplied in high strength steel cylinders, under sufficient pressure to liquefy the chlorine. When chlorine is required, simply opening the valve allows rapid vaporization of the liquid.

There are two basic types of gas chlorinators: direct feed and solution feed. The former allows chlorine gas, under pressure, to be fed directly into the water to be disinfected. Solution feed units mix the gas with a side-stream of water to form a solution of hypochlorite, which then is mixed with the main stream.

Disinfection With Sodium Hypochlorite Solutions

Liquid chlorinators meter a previously prepared hypochlorite solution directly into the water to be disinfected. If the water supply system cannot afford the capital costs and potential risks associated with storing and handling chlorine gas, solutions of sodium hypochlorite can be purchased. It must be remembered that sodium hypochlorite solutions do not contain the concentrations of chlorine available in cylinders of chlorine gas. Additionally, hypochlorite solutions decompose if stored for prolonged periods. As a result, a small water system should plan to store no more than a one-month supply.

In recent years, methods for on-site electrolytic generation of aqueous solutions of hypochlorite have been developed. In a two-cell unit, a brine solution (salt in water) is electrolyzed, producing a solution of hypochlorous acid in one cell and a solution of caustic (sodium hydroxide) in the other:

$Na^+ + Cl^- +$
sodium
chloride

$2H_2O + e^- \longrightarrow HOCl +$
hypochlorous
acid

$NaOH + H_2$

sodium hydroxide   hydrogen

The advantages of this procedure are that purchasing and storing of gaseous chlorine and hypochlorite solutions are avoided. The primary disadvantages are the generation of hydrogen (which poses fire and explosion hazards) and the need to dispose of the caustic generated. In addition, the cost per pound, on a chlorine basis, typically is more than double for on-site electrolytic generation of hypochlorite (30 to 35¢/lb) versus the cost of gaseous chlorine (8 to 15¢/lb). However, site-specific considerations may make on-site hypochlorite generation the process of choice.

Disinfection With Solid Calcium Hypochlorite

Solid calcium hypochlorite is stable when properly packaged and sealed. Thus, a water supply system can purchase its annual requirements in a single procurement. Simply mixing the proper amount of solid with the appropriate volume of water to allow metering without clogging of pumps or metering valves is all that is required for use. Normally, an entire drum of calcium hypochlorite is made into solution. This avoids the partial use of a container, with attendant uncertainties of proper resealing and loss of strength.

Disinfection With Chloramines

Chloramines are formed when water containing ammonia is chlorinated, or when ammonia is added to water containing chlorine (hypochlorite or hypochlorous acid). This can be accomplished by adding gaseous ammonia (purchased as the anhydrous liquid, NH_3, in 150 lb cylinders) directly to the water, or by adding a solution of ammonium sulfate, $(NH_4)_2SO_4$, (purchased in 100 lb bags, 98% pure; 25% available NH_3).

Chemistry of Chloramination

Three chloramine compounds can be produced, depending upon the ratios of chlorine and ammonia which are utilized:

$$NH_3 + HOCl \rightarrow H_2O + NH_2Cl \quad \text{monochloramine}$$

$$NH_2Cl + HOCl \rightarrow H_2O + NHCl_2 \quad \text{dichloramine}$$

$$NHCl_2 + HOCl \rightarrow H_2O + NCl_3 \quad \text{nitrogen trichloride}$$

The distribution of the chemical species of chloramines is a function of pH and of the amount of chlorine added. For example, in the pH range of 7 to 8 and a chlorine to ammonia weight ratio of 3:1, monochloramine is the principal product. At higher chlorine:ammonia ratios or at lower pH values (5 to 7), some dichloramine will be formed. If the pH drops below 5, some nitrogen trichloride (often erroneously called "trichloramine") may be formed. This compound should be avoided because it imparts undesirable taste and odor to the water.

Figure 11 (16) shows the relative percentages of monochloramine and dichloramine produced as the pH changes, for different weight ratios of chlorine to ammonia. At a pH value of about 5.7, approximately equal amounts of mono- and dichloramines are present in solution.

Care also should be taken not to exceed chlorine:ammonia ratios of 5:1. This is the ratio existing at the peak of the breakpoint curve, above which all of the ammonia will have been removed, chloramines will be absent, and free residual chlorine will be present.

Establishing A Chloramine Residual

Generation of chloramines is conducted on-site, in solution, as required, simply by adding the appropriate amount of chlorine to waters already containing ammonia, or by adding ammonia to waters already containing chlorine, then allowing a short holding time to be certain that the chemicals have had time to react with each other to form chloramines. Usually, chloramine-forming reactions are at least 99% complete within several minutes.

Factors Affecting the Disinfection Effectiveness of Chloramine

Mono- and dichloramines ($ClNH_2$ and Cl_2NH, respectively) are effective bactericides, but are much less effective against viruses than is free chlorine. Although dichloramine is about 35 times more powerful a bactericide than is monochloramine (17), both chloramines are less effective bactericides than is free chlorine. For example, at 4°C, 100% inactivation of bacteria required 1.5 mg/L of monochloramine at pH 7.0, and 1.8 mg/L at pH 8.5, after 60 minutes of exposure. By comparison, only 0.03 to 0.6 mg/L of free chlorine was needed at pH ranges of 7.0 to 8.5 at either 4°C or 22°C to achieve 100% bacterial activation in 20 minutes (18).

Laboratory studies have demonstrated that there is limited virus inactivation after the added

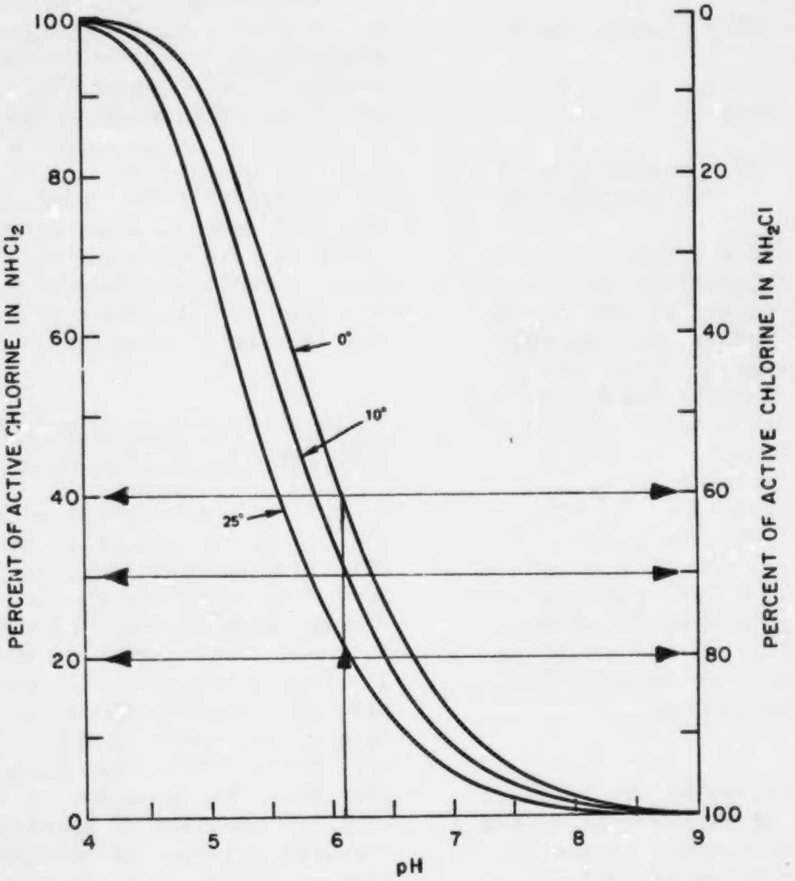


Figure 11. Proportions of Mono- and Dichloramine (NH_2Cl and $NHCl_2$) in Water Chlorination with Equimolar Concentrations of Chlorine and Ammonia (16).

chlorine has reacted with any ammonia that is in the water (having produced chloramines). Most inactivation probably occurs in the first few seconds before the chlorine has completed its reaction with ammonia (19), when chlorine is added to the water before ammonia.

Changes in pH values cause differences in the ratios of mono- and dichloramines present. The stronger disinfectant (dichloramine) will be formed in higher yield at pH values above 5.7 (see Figure 11). Although different studies show mixed results when comparing dichloramine and monochloramine with indicator organisms and other types of organisms, the important observation remains that these differences are more of a scientific curiosity than of any engineering treatment value at this time. However, the observation that chloramines are more stable than free chlorine is important, particularly to small systems which are not as likely to be under 24-hour surveillance. Chloramines will persist in distribution systems where their protection is very much needed.

Effective disinfection using chloramine treatment is even more complex than when using free chlorine, because virtually all of the factors that pertain to free chlorine treatment apply, plus additional considerations:

- o the raw water quality must be superior in terms of the absence of pathogenic viruses and cysts. The presence of either of these virtually requires the use of free chlorine and perhaps additional treatment by chemicals and filtration prior to chlorination;
- o the time of contact must be long, being measured in terms of hours rather than minutes;
- o organic chloramines will form if proteinaceous materials are present, which will give a combined residual reading by an analytical test; however, these are not as effective bactericidal agents as are monochloramine and dichloramine. Hence the actual concentration of mono- and dichloramines will be less than indicated bv the analytical test.

Chloramine treatment best follows the principles of use of free chlorine. Such treatment has been used effectively by many water supply systems for many years, primarily to reduce levels of chlorinous tastes. In recent years it has become apparent that the use of free chlorine may result in the production of undesirable trihalomethane compounds, if their required precursors are present in the water. Therefore, those small water supply systems wishing to utilize chloramines, but planning to add chlorine prior to addition of ammonia should plan to check the formation of THMs under this mode of chloramine generation, before adopting this procedure.

By-Products of Chloramination

No detrimental reaction products of chloramine use are known, except for nitrogen trichloride, which imparts disagreeable taste and odor to the water, and may be toxic to humans as well. The use of the proper amounts of each chemical reactant will avoid its production.

Chloramines do not produce THMs, unless in the presence of free chlorine. Therefore, one advantage of adding chlorine to an ammonia-containing water is that a free residual can be avoided and no trihalomethanes created. If this technique provides the necessary level of disinfection, it will be a low cost method of meeting TTHM limitations.

An advantage of chlorinating to a free residual, and then adding ammonia to convert the free residual to a combined chloramine residual is that the full advantages of free chlorine disinfection can be attained in the treatment plant prior to forming the weaker combined residual. If the levels of TTHMs thus produced in the treatment plant are sufficiently low, then converting to a combined residual by adding ammonia first prior to the distribution system will insure that higher TTHM levels will not result.

Disinfection With Chlorine Dioxide

Chlorine dioxide (ClO_2), an unstable, greenish-yellow gas is explosive in air at concentrations above 11%. Because of its instability, it is generated in solution, on-site, and is used immediately. As long as care is taken to keep chlorine dioxide in solution and storage of solutions is avoided, there are no potential explosion hazards. Chlorine dioxide is readily soluble in water and is decomposed by sunlight.

Like chloramine, chlorine dioxide has enjoyed increased usage in treating water supplies in recent years for several reasons. First, it is a more effective biocidal agent than is chlorine or hypochlorous acid. When prepared in the absence of excess free residual chlorine, application of chlorine dioxide will not produce THMs. Additionally, chlorine dioxide can be used in pretreatment to oxidize phenolic compounds and to separate iron and manganese from organic complexes, some of which are stable to chlorination. Similar to chlorine and chloramines, chlorine dioxide provides a protective residual in distribution systems. This residual is longer lasting than that of chlorine, because chlorine dioxide does not react with ammonia. It is not known to impart tastes and odors, as does chlorine.

Chemistry of Chlorine Dioxide

For drinking water treatment, chlorine dioxide is generated from sodium chlorite, $NaClO_2$. This material, purchased as a solid (80% $NaClO_2$) or in 28 to 30% aqueous solution, is treated with aqueous solutions of chlorine or hypochlorous acid, sometimes in the presence of an added strong mineral acid, such as sulfuric or hydrochloric acid.

Three processes used in water treatment plants for the synthesis of ClO_2 from sodium chlorite employ (a) gaseous chlorine, (b) sodium hypochlorite solution and mineral acid, and (c) mineral acid. Each process is summarized below:

Gaseous Chlorine -- This is a two-step procedure, beginning with the formation of hypochlorous acid by dissolution of chlorine into water:

$$\underset{\text{chlorine}}{Cl_2} + \underset{\text{water}}{H_2O} \longrightarrow \underset{\text{hypochlorous acid}}{HOCl} + \underset{\text{hydrochloric acid}}{HCl}$$

These intermediate products then react with sodium chlorite to form chlorine dioxide:

$$HOCl + HCl + \underset{\text{sodium chlorite}}{2NaClO_2} \longrightarrow \underset{\text{chlorine dioxide}}{2ClO_2} + \underset{\text{sodium chloride}}{2NaCl} + H_2O$$

The end result of these reactions is summarized by the equation:

$$\underset{\text{chlorine}}{Cl_2} + \underset{\text{sodium chlorite}}{2NaClO_2} \longrightarrow \underset{\text{chlorine dioxide}}{2ClO_2} + \underset{\text{sodium chloride}}{2NaCl}$$

According to this equation, one mole of chlorine reacts with two moles of $NaClO_2$ to produce two moles of chlorine dioxide. In water supply practice, excess chlorine is employed, so as to insure conversion of the maximum amount of chlorite ion to chlorine dioxide. Therefore, the recommended ratios of reactants is two moles of chlorine to one mole of sodium chlorite. On a weight basis, 1.57 parts of chlorine gas are added per part of $NaClO_2$ (calculated on a 100% solids basis when solutions of sodium chlorite or 80% solids materials are employed).

Under these conditions of excess chlorine gas being added, the product ClO_2 solution also will contain an amount of hypochlorous acid/hypochlorite ions. These can react with THM precursor materials to produce THMs.

Sodium Hypochlorite and Mineral Acid -- This also is a two-step reaction, in which sodium hypochlorite reacts with hydrochloric acid to form hypochlorous acid, which then reacts with sodium chlorite to form chlorine dioxide:

$$\underset{\text{sodium hypochlorite}}{NaOCl} + \underset{\text{hydrochloric acid}}{HCl} \longrightarrow \underset{\text{sodium chloride}}{NaCl} + \underset{\text{hypochlorous acid}}{HOCl}$$

$$\underset{\text{hypochlorous acid}}{HOCl} + \underset{\text{hydrochloric acid}}{HCl} + \underset{\text{sodium chlorite}}{2NaClO_2} \longrightarrow \underset{\text{chlorine dioxide}}{2ClO_2^-} + \underset{\text{sodium chloride}}{2NaCl} + \underset{\text{water}}{H_2O}$$

In this procedure as in the gaseous chlorine and sodium chlorite procedure, excess chlorine is utilized to insure conversion of the maximum amount of chlorite ion to chlorine dioxide. The ClO_2 solution also will be able to produce some THMs.

Mineral Acid -- This process involves mixing a solution of acid with a solution of $NaClO_2$. The reaction of sodium chlorite with hydrochloric acid can be depicted by the equation:

$$\underset{\text{sodium chlorite}}{5NaClO_2} + \underset{\text{hydrochloric acid}}{4HCl} \longrightarrow \underset{\text{chlorine dioxide}}{4ClO_2} + \underset{\text{sodium chloride}}{5NaCl} + \underset{\text{water}}{2H_2O}$$

The reaction of sodium chlorite with sulfuric acid solution can be depicted by the equation:

$$\underset{\text{sodium chlorite}}{10NaClO_2} + \underset{\text{sulfuric acid}}{5H_2SO_4} \longrightarrow \underset{\text{chlorine dioxide}}{8ClO_2} + \underset{\text{sodium sulfate}}{5Na_2SO_4} + \underset{\text{water}}{4H_2O} + \underset{\text{hydrochloric acid}}{2HCl}$$

The exact ratios of reactants will depend upon which mineral acid is employed for the production of ClO_2.

When generated from either mineral acid, excess chlorine is not required. Therefore, solutions of chlorine dioxide prepared in this manner do not contain free residual chlorine.

In all three cases, the appropriate aqueous solutions of reactants are metered into a chlorine dioxide reactor (a cylinder containing Raschig rings or glass beads) where intimate mixing of the reacting solutions occurs (see Figures 15 and 16 in Section 4). The size of the reactor and the residence time of the reacting solutions are such that after a few seconds the solution exiting from the reactor shows the strongly yellow color of dissolved chlorine dioxide. This solution is pumped directly into the water to be treated.

In this manner, solutions of chlorine dioxide are generated as the material is required and used immediately, without storage. Appropriate metering and control instrumentation can be installed with the ClO_2 reactor so that the generation and addition of chlorine dioxide is paced by the flow rate of the water to be treated. As a result, the unit operates without the need of constant attention.

Oxidation-Reduction Reactions of Chlorine Dioxide -- Chlorine dioxide does not react with water itself, as does chlorine. On the other hand, when performing its function of a chemical oxidant, chlorine dioxide is reduced. One of the reduction products that is produced is reformation of the chlorite ion from which the ClO_2 was formed initially:

$$\underset{\text{chlorine dioxide}}{ClO_2} + e^- \longrightarrow \underset{\text{chlorite ion}}{ClO_2^-}$$

It also can disproportionate (undergo self-oxidation and reduction) to form chlorite and chlorate anions:

$$\underset{\text{chlorine dioxide}}{2ClO_2} + \underset{\text{water}}{H_2O} \longrightarrow \underset{\text{chlorite ion}}{ClO_2^-} + \underset{\text{chlorate ion}}{ClO_3^-} + \underset{\text{hydrogen ion}}{2H^+}$$

Disproportionation reactions of chlorine dioxide normally occur rapidly at low and/or high pH ranges (pH below 2 and above 11). Thus, in normal water supply systems, where these pH ranges are not encountered, disproportionation products should not be observed.

Establishing a Chlorine Dioxide Residual

Because the cost of chlorine dioxide is higher than that of chlorine, and because of the potential toxicity of chlorite ion to humans (see below), only small dosages of chlorine dioxide (maximum of 1 mg/L) currently are recommended by EPA for drinking water treatment (11). However, a primary advantage of chlorine dioxide is that it does not react with ammonia, as does chlorine. This means that if water has been pretreated to remove most of the oxidant-demanding consituents (or does not contain them initially), the 1 mg/L or less dosage of chlorine dioxide can be utilized almost totally for providing disinfection. Stable residual concentrations of chlorine dioxide can be maintained in distribution systems under such conditions.

For these same reasons of cost and possible toxicity, its use as a predisinfectant should not be considered if it is also to be used as a post-disinfectant. This is because if chlorine dioxide is used for both purposes, the recommended maximum dosage of 1 mg/L will have to be exceeded, in all likelihood.

Factors Affecting the Efficiency of Disinfection With Chlorine Dioxide

Chlorine dioxide is more effective than chlorine or hypochlorous acid as a disinfectant. Because it does not react with water, ammonia or most organic nitrogenous compounds, it is not "wasted" in extraneous reactions of this type. It is less sensitive to changes in pH (except for very low and very high values), maintaining its capabilities to disinfect over the pH range of 6 to 10.

On the other hand, because it is a more powerful oxidizing agent than chlorine, hypochlorous acid or chloramines, chlorine dioxide can and will react with oxidizable impurities contained in a raw water. Thus, it is important to ensure that oxidant-demanding components of the water have been removed to as low a level as is feasible, consistent with the costs involved.

By-Products of Chlorine Dioxide Use

When chlorine dioxide is generated free of excess chlorine (mineral acid procedure), and used as a disinfectant, it will not produce THMs, even if the water being treated has unsatisfied THM formation potential (THMFP). On the other hand, ClO_2 can give rise to oxygen-containing organic oxidation products. Many of the organic oxidation products of chlorine dioxide have been identified, but others may form which have not yet been identified. The prudent water treatment plant operator will recognize the uncertainties involved and design for addition of ClO_2 at the point in his treatment process where concentrations of oxidant-demanding materials are lowest, and where he will derive the maximum benefit from the small dosage (1.0 mg/L) of chlorine dioxide currently recommended by EPA.

Toxicity of Chlorine Dioxide

The gaseous material has a strong, disagreeable odor, similar to that of chlorine gas, and is toxic to humans when inhaled. It is detectable by the human nose at concentrations between 1.4 and 1.7%. When present at 4.5%, it irritates respiratory mucous membranes and may cause severe headaches. At concentrations below 6% in air, it may be compared to chlorine, with respect to its toxicity (20). Eventual intoxications appear by local irritations of the nervous system, ocular and respiratory mucous membranes, without substantial resorption or systemic poisoning (21). There are no cumulative effects in cases of repeated exposure (22).

Disinfection With Ozone

Ozone (O_3) is a very strong chemical oxidizing agent, second in oxidizing power only to elemental fluorine among the readily available chemicals. Because of its oxidizing ability, ozone also is a powerful disinfecting agent. Ozone is an unstable gas at ordinary temperatures, and decomposes rapidly at temperatures above 35°C. For this reason, it cannot be manufactured and packaged at a central manufacturing plant, as can chlorine. Therefore, like chlorine dioxide, ozone must be generated on-site and used immediately.

For the on-site generation of ozone, an oxygen-containing gas (air, oxygen-enriched air or pure oxygen) is dried and cooled, then passed between two electrodes separated by a discharge gap and a dielectric material across which high voltage potentials are passed. In recent years, some ozone generation equipment has been modified to operate at high frequencies rather than at high voltages. Figure 12 is a schematic diagram of the essential components of a corona discharge ozone generator, the type available commercially which produces sufficient quantities of ozone for use in water and wastewater treatment plants.

For small water treatment plants, dried air will be the source gas

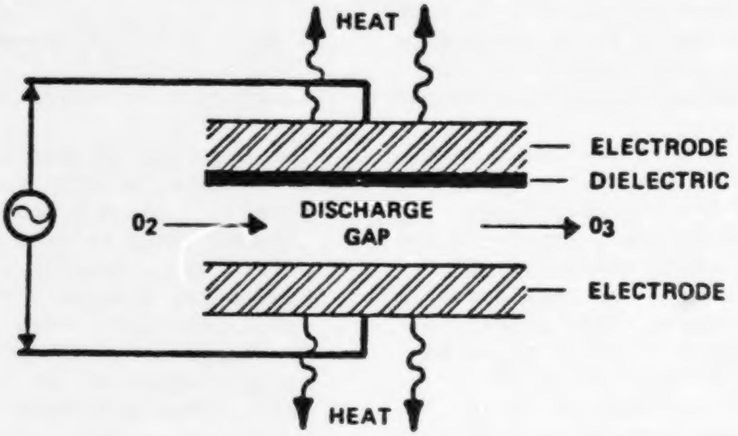

HEAT
ELECTRODE
DIELECTRIC
O_2
DISCHARGE GAP
O_3
ELECTRODE
HEAT

Figure 12. Typical Corona Cell Ozone Generator Configuration (23)

fed to the ozone generator. Under such conditions, the output from an ozone generator will be dried, cooled air containing 1 to 2% of ozone, which is partially soluble in water (about 20 times as soluble as oxygen). This mixture of ozone in air then must be mixed (by a process called contacting) with the water to be treated. This is accomplished by means of porous diffusers placed at the bottom of a contact chamber, or by means of turbines, injectors, or high speed agitators. In some cases, the water to be treated is sprayed through a small orifice into an ozone-containing atmosphere.

Ozone has a characteristic odor which can be detected by most humans at low concentrations (0.01 to 0.05 ppm), far below the levels of acute toxicity. Olfactory fatigue has been noted in some instances. This means that as the length of exposure to an ozone-containing atmosphere increases, the odor of ozone becomes less noticed by smell.

In distilled water, ozone has a half-life (the time for 50% of it to disappear by decomposition) of about 160 minutes at 20°C. However, in colder water, the half-life of ozone is longer.

Chemistry of Ozone

When an oxygen-containing gas is passed through an ozone generator, part of the oxygen dissociates as a result of being exposed to the high energy electrical field of the corona discharge:

$$\underset{\text{oxygen}}{O_2} + e^- \longrightarrow 2[O] \quad \text{"fragments"}$$

These oxygen "fragments" are highly reactive, and they combine rapidly with molecular oxygen, forming the triatomic molecule, ozone:

$$\underset{\substack{\text{oxygen}\\\text{fragments}}}{2[O]} + \underset{\text{oxygen}}{2O_2} \longrightarrow \underset{\text{ozone}}{2O_3}$$

The overall reaction to produce ozone is the sum of the above reactions:

$$\underset{\text{oxygen}}{3O_2} + \underset{\text{energy}}{e^-} \longrightarrow \underset{\text{ozone}}{2O_3}$$

The reaction to produce ozone is reversible, meaning that once formed, ozone decomposes back to oxygen. This reverse reaction occurs quite rapidly above 35°C. Therefore, because reactions involving high energy electrical discharges also are accompanied by generation of considerable heat, ozone generators are designed to provide a high degree of cooling, in order to minimize ozone losses by decomposition.

Uses of Ozone in Water Treatment

Because ozone is such a powerful chemical oxidant, it is used for a number of applications in the treatment of drinking water. This short-lived oxidant reacts with a wide variety of organic and inorganic pollutants in water, as well as being a very fast acting and effective disinfectant. It has been in use as a water treatment chemical since 1906, primarily in Europe in more than 1,000 water treatment plants, although at least 15 U.S. water treatment plants currently are employing ozone. Some of the applications of ozone in drinking water treatment are: disinfection; pretreatment for oxidation of organics; as a flocculant aid; for taste, odor and color removal; and for oxidation of a range of organic and inorganic materials (iron, manganese, sulfides, cyanides, etc.).

Ozone provides almost instantaneous bacterial disinfection and viral inactivation after only a few minutes of continuous contact with the water being treated.

Factors Affecting the Disinfecting Efficiency of Ozone

It should be recognized that because ozone is such a powerful oxidizing agent, it is not particularly selective. In other words, if ozone is used early in the water treatment process, for example, to oxidize iron and manganese, a high degree of disinfection also will be obtained. Conversely, if ozone is used at the end of the water treatment process for disinfection, it also will oxidize any easily oxidizable materials still present. The same can be said of chlorine dioxide and chlorine. Thus when employing any strong chemical oxidizing agent as a disinfectant, the better job the pretreatment process can do to lower the "oxidant demand" of the water, the less disinfectant will be required and the fewer disinfectant by-products will be formed.

Ozone is affected little by changes in water temperatures or pH, and it does not react with water as does chlorine. Also, ozone does not react rapidly with ammonia except above pH 9. However, ozone does have a short half-life in water. This means that ozonized waters will not have a lasting residual in the distribution system. Although there are a number of European, Canadian, and even two U.S. plants which do use ozone as the terminal disinfectant, these are the exception rather than the rule. In those cases in which ozone is the last treatment step, a combination of factors must occur simultaneously (24):

- cool water temperature;
- clean and short distribution system;
- short residence time (less than 12 hours);
- low levels of organics;
- no ammonia present.

In all other cases, a disinfectant which provides a stable residual is added after ozone has been utilized as the primary disinfectant. The advantage of employing ozone as the primary disinfectant is that much smaller dosages of chlorine, chlorine dioxide or chloramines then must be added, usually less than 0.5 mg/L to provide a stable residual for the distribution system.

In applying ozone as a disinfectant, the customary European practice is to utilize a two-chamber contacting apparatus. In the first chamber, the ozone demand of the water is satisfied and the dissolved residual ozone level is brought to a level of 0.4 mg/L. In the second contact stage, the 0.4 mg/L level is maintained over a minimum period of four minutes. These conditions have been shown by Coin *et al.* (25,26) to provide at least 99.99% inactivation of Polioviruses Types I, II and III, and to kill bacteria as well.

The use of two contact chambers allows economy in the amounts of ozone to be added. About two-thirds of the total ozone required is added to the first stage (which contains water having the highest ozone demand). Once the ozone demand has been satisfied, however, much less ozone is required to maintain the 0.4 mg/L residual over the four minutes subsequent contact time.

Establishing an Ozone Residual

Although a residual level of ozone can be established in the contact chambers, which is sufficiently stable to allow measurement to conform with the four minutes/0.4 mg/L criteria for disinfection, this residual rapidly dissipates and, generally, can not be maintained in the distribution system. During ozonation, considerable oxygen is added and many of the dissolved organic impurities present in trace or higher concentrations will be rendered more readily biodegradable. This occurs because during ozone oxidation, oxygen atoms become chemically bound into the organic contaminants. The partially oxidized organic materials are now more readily assimilated by aerobic microorganisms present in the water.

As a result of ozonation, therefore, biological aftergrowths can occur more readily in distribution systems. For this reason, most water treatment plants using ozone for disinfection also add small quantities of chlorine dioxide, chlorine, or chloramine. As indicated earlier however, considerably smaller dosages of these residual-forming disinfectants need be employed. In European water treatment plants, large or small, the dosages of residual chemicals rarely exceed 0.5 mg/L.

Oxidation By-Products of Ozonation

Although ozone is chemically incapable of producing chlorinated organic by-products, nevertheless there is the potential for generating other organic materials, some of which may pose hazards to the public health. This is all the more recognizable when it is realized that the small quantities of ozone used in drinking water treatment processes rarely are sufficient to oxidize organic materials completely to carbon dioxide and water.

As a general principle, those organic compounds which can be oxidized by ozone will be oxidized to materials which contain more oxygen in their structures. This makes the oxidized products more easily flocculated and coagulated. In addition, oxygen incorporated into organic structures generally increases the biodegradability of organic compounds. Thus, ozonation also produces food for microorganisms which may find their way into the treated water after the ozone residual has dissipated.

Some organic compounds may be oxidized by ozone to produce new compounds which are more toxic than are their predecessors. For example, oxidation of the pesticides heptachlor, malathion, and parathion with ozone produces, respectively, heptachlorepoxide, malaoxon and paraoxon as the first oxidation products. All three of these materials are of higher toxicity than their precursors. Although malaoxon and paraoxon then continue to be oxidatively destroyed upon continued ozonation, heptachlorepoxide is quite stable to continued ozonation.

It is important to recognize that the production of these specific intermediate oxidation products may not be caused solely by the use of ozone. It is possible that chlorine dioxide and chlorine may produce the same intermediates. Thus the discerning water treatment official should attempt to know what contaminants are present in his water supply, as well as the chemistries of the disinfectant/oxidant options available to him. Armed with this information, he then will be better able to determine the most cost-effective method for dealing with his specific problem.

Toxicity of Ozone

In aqueous solution, ozone is a powerful oxidizing agent which will react with human tissues. Therefore, the lack of a stable residual in water is a benefit, in that by the time ozonized water reaches a consumer's tap, there should be no dissolved residual of ozone. Therefore, from the standpoints of toxicity and cost, it is important for plant operators using ozone not to add excessive amounts of ozone in an attempt to maintain an ozone residual in the distribution system (see case history on Strasburg, PA).

In the ambient plant air, ozone can cause temporary discomfort for plant operators. Therefore, precautions should be taken to detect any leakages of ozone from the generating units or from the contacting chambers. This can be accomplished conveniently by installing an ambient air ozone monitor in the ozone generating/contacting room. This monitor can be coupled electronically with the ozone generator, and an alarm, so that in the event ozone is detected in the plant ambient air, electrical power to the ozone generator will be cut off, thus ceasing the generation of ozone, and sounding an alarm. This subject is treated in more detail in Section V.

Disinfection With Ultraviolet Radiation

Ultraviolet radiation is an effective disinfecting agent against bacteria and viruses, but it is not effective against spores and cysts. It has been used commercially for many years in pharmaceutical houses, cosmetics manufacturing plants, beverage production, aquaculture, and the semiconductor industry to disinfect large volumes of better-than-potable quality waters. In addition, UV radiation has the additional advantage of not being a chemical oxidant. Therefore, microorganisms can be killed without generating by-products of chemical oxidation or halogenation.

In practice, however, UV-generating units also generate small quantities of ozone, which can produce trace amounts of organic oxidation products.

Two drawbacks have been cited against the use of UV radiation for disinfecting potable water supplies on a large scale, neither of which is entirely correct. The first is that UV radiation provides no stable residual in the distribution system. This is of little consequence, since small amounts of chlorine, chlorine dioxide or chloramine can be added for that purpose. For example, UV radiation is allowed for disinfection aboard ships, but new shipboard regulations require the use of chlorine as well.

The second objection is the erroneous belief that only thin films of water can be disinfected effectively by UV radiation, thus posing difficult engineering design problems for treating larger quantities of water.

Modern UV radiation units contain multiple tubes which are arranged around the periphery of the units. Water to be disinfected flows through these units following baffled paths, thus allowing adequate contact times and repeated exposure to the UV radiation. Figure 13 is a schematic diagram of a typical assemblage of ultraviolet radiation equipment for treatment of water and wastewater. As with the use of any other disinfectant, the better the pretreatment of the water, the more efficient will be the disinfection efficiency of UV radiation.

Factors Affecting Disinfection Efficiency of UV Radiation

In order for any radiation to kill or inactivate a microorganism, it is essential for the radiation to reach the microorganism. Thus, anything which prevents radiation from striking the microorganism, alters the wavelength of the radiation, or decreases the quantity of radiation striking the microorganism, will interfere with the disinfection process. Examples include:

- films or coatings which develop on the surfaces of UV lamps;
- agglomerations of organisms in which the inner organisms are protected from the radiation;
- suspended materials in the water (turbidity);
- colored water that can attenuate the radiation;
- dissolved organics that absorb the radiation;
- decrease in time of exposure to radiation -- by short-circuiting of water flowing through the exposure chamber.

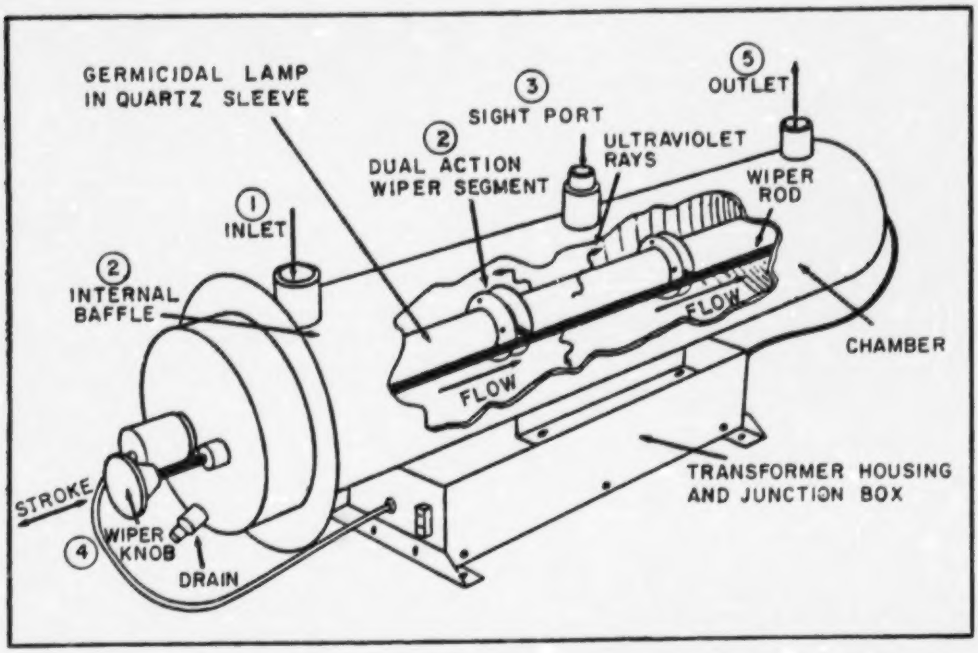
There also is a phenomenon associated with UV-damaged cells called photo-reactivation. Upon exposure to sunlight, some damaged cells can repair damage they may have sustained, and then continue normal metabolism (e.g., living).

By-Products of UV Radiation

From the point of view of disinfection of drinking water, there are no chemical by-products of UV radiation, other than those trace quantities of organic oxidation products which may be produced by the small quantities of ozone formed as a by-product of UV radiation.

Hazards of UV Radiation

Damage to human eyes is the major hazard from the use of UV radiation. All reputable suppliers of UV generating equipment have taken this factor into account in designing their equipment. Thus, during operation, no "leaks" of light should be observable by the water treatment plant operator.


GERMICIDAL LAMP IN QUARTZ SLEEVE
③
SIGHT PORT
⑤
OUTLET
②
DUAL ACTION WIPER SEGMENT
ULTRAVIOLET RAYS
WIPER ROD
①
INLET
②
INTERNAL BAFFLE
FLOW
FLOW
CHAMBER
TRANSFORMER HOUSING AND JUNCTION BOX
STROKE
WIPER KNOB
④
DRAIN

PRINCIPLE OF OPERATION

1 The water enters the purifier and flows into the annular space between the quartz sleeve and the outside chamber wall.

2 The internal baffle and wiper segments induce turbulence in the flowing liquid to insure uniform exposure of suspended micro-organisms to the lethal ultraviolet rays.

3 The sight port enables visual observation of lamp operation.

4 The wiper assembly facilitates periodic cleaning of the quartz sleeve without any disassembly or interruption of purifier operation.

5 Water leaving the purifier is instantly ready for use.

Figure 13. Schematic Diagram of Ultraviolet Radiation Disinfection Systems. (Courtesy of Pure Water Systems)

IV. DISINFECTION SYSTEM DESIGN

INTRODUCTION

Water utilities normally require the services of an experienced consulting engineer or equipment vendor for design of disinfection systems and other portions of a water treatment system to obtain the necessary approval of the state agency having primary enforcement responsibility for safe drinking water. The scope of services of the consultant or the vendor's professional staff can be tailored to fit the needs of the particular water utility, but may include some or all of the following services:

- Preliminary Study
- Preliminary Design
- Detailed Design
- Construction Supervision
- Startup Assistance

A high level of rapport must be established between representatives of the utility and the engineer. The engineer must be familiar with the unique features and requirements of the utility as well as responsiveness of the regional chemical suppliers and equipment vendors prior to proceeding to the detailed design stage of the work.

This section presents discussions of the factors important from the design viewpoint in selection of a disinfectant, the specific design features of each of the disinfectants in use today, then a discussion of the provisions necessary for the safe use of these disinfectants.

OPTIMAL SYSTEM DESIGN

The designer of a water treatment plant can ease the job of the operator and also help lessen the probability of error by following some simple rules:

- Conduct sufficient laboratory and pilot plant studies and observations of the source waters to fully characterize them. Raw water quality in many areas is declining due to more extensive use, and this must be anticipated in the design. New facilities should be adequate to handle the full range of expected water conditions, which includes foreseeable water quality deterioration.

- Initiate the design process with a thorough review of all possible non-treatment or minimal treatment approaches. Include consideration for ease of maintenance, adequate space and light, and simplicity in the design and equipment. Avoid overly elaborate control systems and include appropriate redundance (i.e., never only one chlorinator).

- Avoid dead ends in the distribution system. Provide equipment for flushing and sampling, for storage, and for emergency chlorination of the distribution system. Clearly identify such emergency equipment, for example, by the use of color-coded paints.

SELECTION OF A DISINFECTANT

The selection of a disinfectant and/or oxidant depends upon a wide range of factors which include the following:

- raw water characteristics;
- facility design flow - peak, average, minimum;
- overall treatment system requirements and complexity;
- distribution system characteristics;
- consumer needs and preferences;
- cost-effective analyses;
- equipment supplier representation;
- chemical supplier reliability;
- regulatory agency acceptance; and
- site-specific problems, which include
    a. sludge disposal
    b. power availability
    c. facility access
    d. safety

Raw water quality, design flow, and finished water requirements are key factors in the selection of the disinfectant(s) and/or oxidant(s) to be used in the treatment process. A highly complex treatment system may be required to produce drinking water from a low quality raw water source. This finished water must conform to regulatory agency standards and be acceptable to the consumer. This type of system likely would require the ability to operate a sophisticated disinfection/oxidation system or systems. In the same manner, larger plants normally may justify more complete disinfection systems while small ones may not. Once regulatory agency requirements have been satisfied, finished water parameters such as those for taste, odor, color, and dissolved organics become a matter of consumer acceptance. In specific cases, such as in Strasburg, Pennsylvania (see Section 8, CASE HISTORIES) and Whiting, Indiana (27), consumer demands forced the installation of ozone rather than chlorine, while consumer demand in Hamilton, Ohio, caused the adoption of chlorine dioxide in place of chlorine (28).

Factors unique to the specific treatment plant may dictate disinfectant selection. Facilities which have a sludge disposal problem might seek to reduce the problem by testing the benefit of adding ozone early in the process as a coagulant aid as well as an oxidant. Limited availability of power at the point of disinfection could eliminate ozonation as a disinfection alternative. Limited site access during all or parts of the year might favor the use of disinfectants/oxidants generated on-site. The use of bottled chlorine as a disinfectant has been precluded in certain areas due to safety concerns.

The quantity of disinfectant/oxidant to be used is governed by the oxidant demand of the water to be disinfected and by the characteristics of the water distribution system. Maintenance of a required residual level of disinfectant in the extremities of a sprawling water distribution system with long water retention times requires large post-treatment disinfectant dosages for finished waters having high oxidant demands.

Cost-effectiveness considerations, operator acceptance, and equipment vendor representation are three remaining factors in the selection process. In varying degrees, all systems are sensitive to the disinfectant/oxidant dosage required, both in terms of initial capital investment and of continuing operation and maintenance costs. Provision of a disinfection (or even treatment) system which the utility staff will not accept or which is beyond its capabilities to operate and maintain is of questionable benefit to the waterworks. Difficult to quantify, but frequently of great importance to the operator, is the posture of the local representation of various system vendors and chemical suppliers.

CHLORINATION SYSTEM DESIGN

Choice of the form of chlorination system to be used; whether gaseous chlorine (Cl_2), dry calcium hypochlorite [$Ca(OCl)_2$], or sodium hypochlorite solution (NaOCl) depends upon a number of factors which include the following:

- availability of chlorine source chemical;
- capital cost of the facility;
- operation and maintenance costs for the equipment;
- chemical costs;
- location of the facility;
- operator skills available;
- safety.

Each of the methods of chlorination will provide the same disinfecting power on a pound for pound basis of available chlorine when utilized at the same pH. However, each of the systems must be approached differently in terms of basic design and safety. Sufficient chlorine must be provided to satisfy the chlorine demand of the water at the point of chlorine addition, plus an additional amount to maintain the required residual after a specified period of time. The relative dosages of the various chemical sources of hypochlorite ion (OCl^-) in solution can be determined; these frequently will depend upon the point of chlorine application in the process. The chlorine demand of raw water usually is far higher than that of finished water. In any case, a minimum of 20 minutes contact time at the peak water demand rate must be provided between the point of addition of the chlorine to the water and the first customer service in the distribution system. If this contact time is not provided in the distribution system, a baffled holding tank located at the plant or in the system should be provided after chlorination.

Chlorination With Gaseous Chlorine

Chlorine is supplied in high strength steel cylinders with chlorine capacities of 100 and 150 pounds (45.4 and 68.1 kilograms), under sufficient pressure to liquefy the chlorine. Major manufacturers of gaseous chlorine are shown in Table VI. However, the quantity consumed by small treatment facilities normally would be purchased from local suppliers which are listed in the local telephone directory yellow pages under "chemical suppliers" or "swimming pool suppliers".

TABLE VI

MAJOR MANUFACTURERS OF GASEOUS CHLORINE

Name	Address
Allied Chemical Corporation	P.O. Box 1139R, Morristown, NJ 07960
Ashland Chemical Company	P.O. Box 2219, Columbus, Ohio 43216
Pennwalt Corporation	Organic Chemicals Division, Three Parkway, Philadelphia, PA 19101
PPG Industries, Inc.	Chemical Division, One Gateway Center, Pittsburgh, PA 15222
Dixie Chemical Company	3635 W. Dallas Street, Houston, TX 77019

Direct feed chlorinators add gas under pressure directly into the water to be disinfected. This type of unit normally is used only when electrical power is unavailable to operate a solution feed unit. This is an extremely site-specific application which will not be discussed further.

Solution feed units mix chlorine gas with a side stream of water to form a chlorine (hypochlorous acid) solution, which then is injected into the main stream. Solution feed chlorinators operate on a vacuum controlled basis, automatically shutting off if the side stream flow is interrupted. This type of unit, shown in Figure 14, is preferable for safety reasons over direct feed units.

The basic solution feed gas chlorinator includes the following components:

- o isolating valve to interrupt gas flow;
- o pressure regulating valve;
- o gas flow indicator;
- o adjustable gas flow controller;
- o check valve;
- o venturi type gas injector.

The market for supply of gas chlorinators is extremely competitive, as illustrated by Table VII which provides a partial list of suppliers of these types of units.

Well established standards for design of gas chlorination systems exist in standard waterworks industry literature (29,30). The following points are provided to highlight possible design questions:

- o Under normal conditions, the maximum withdrawal rate of chlorine gas (40 lbs/day - 18.16 kg/day) from a single 150 lb (68.1 kg) liquid

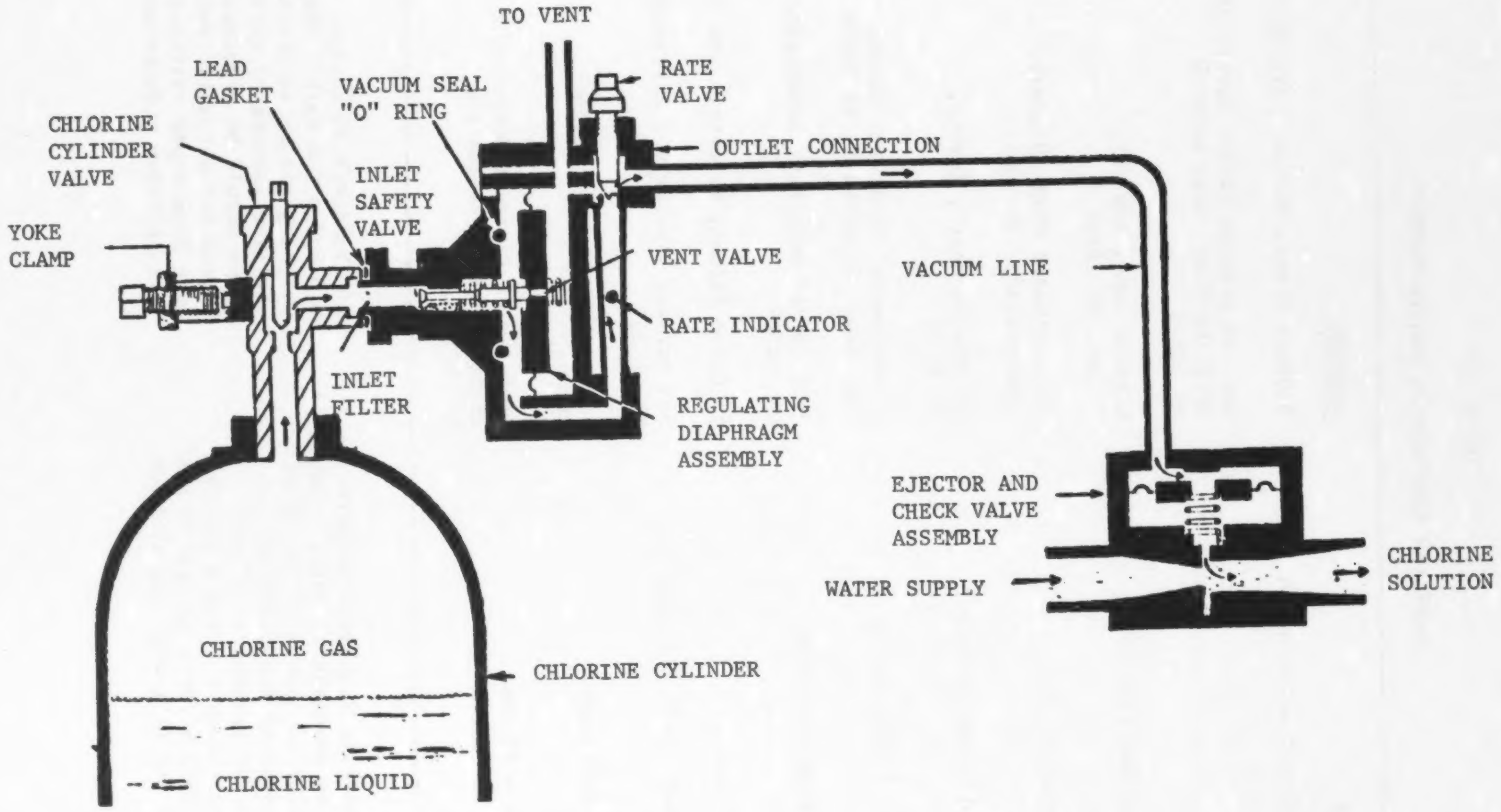

TO VENT
LEAD
GASKET
VACUUM SEAL
"O" RING
RATE
VALVE
CHLORINE
CYLINDER
VALVE
OUTLET CONNECTION
INLET
SAFETY
VALVE
YOKE
CLAMP
VENT VALVE
VACUUM LINE
RATE INDICATOR
INLET
FILTER
REGULATING
DIAPHRAGM
ASSEMBLY
EJECTOR AND
CHECK VALVE
ASSEMBLY
CHLORINE
SOLUTION
WATER SUPPLY
CHLORINE GAS
CHLORINE CYLINDER
CHLORINE LIQUID

Figure 14. Solution Feed Gas Chlorination System

TABLE VII

SOME GAS CHLORINATOR MANUFACTURERS

Name	Address
Air-O-Lator Corporation	8100-04 Paseo, Kansas City, MO 64131
BIF	Unit of General Signal Corp., 1600 Division Road, West Warwick, RI 02893
Capital Controls Co.	Advance Lane, Box 211, Colmar, PA 18915
Chlorinators, Inc.	733 Northeast Dixie Highway, Jensen Beach, FL 33457
Diamond Shamrock Corp.	351 Phelps Court, Irving, TX 75062
Fischer & Porter, Co.	Environmental Division, County Line Road, Warminster, PA 18974
Force Flow Equipment	3567 Golden Gate Way, Lafayette, CA 94549
Ionics, Inc.	65 Grove Street, Watertown, MA 02172
ProMinent Fluid Controls	503 Parkway View Drive, Pittsburgh, PA 15205
Tait-Andritz Inc.	4601 Locust Street, Lubbock, TX 79404
Wallace & Tiernan	Division of Pennwalt Corporation, 25 Main Street, Belleville, NJ 07109

chlorine container is more than adequate to satisfy the chlorine demand of the water processed for 5,000 persons (5,000 persons x 100 gal/capita/day = 500,000 gal/day = 1893 m^3/day) as illustrated by the following calculation: 40 lbs/day/8.34 lbs/gal x 0.5 mgd = 9.6 mg/L. However, weighing scales to provide a positive measure of chlorine usage should be provided. A device for automatic switch-over from empty cylinder to full cylinder reduces manpower requirements and increases chlorination reliability.

- Chlorine cylinders are heavy and bulky, even when empty. Provision should be made for easy removal of gas cylinders from the delivery truck and their movement to the chlorine storage room. A special cart should be assigned to the chlorination facility for cylinder transport. Stairways, narrow doorways and passages should not be part of the route from delivery to storage. Any cylinders stored upright should be securely fastened to the walls to prevent their falling, which can shear the neck and cause a rapid discharge of the gas - resulting in two hazards - exposure to high concentrations of chlorine and the danger of physical injury from the cylinder, which can become a fast-moving projectile.

- Chlorinators should be located as close as possible to the point of application. Provision should be made for regular inspection of chlorine gas and solution lines.

- The 150-lb (68.1 kg) cylinders should be operated so that chlorine is used at a rate no greater than 40 lbs (18.2 kg) per day per cylinder. If chlorine is removed at a greater rate, evaporation of the liquid chlorine will cool the chlorine, and chlorine lines and valves may freeze and impede flow. Multiple cylinders should be used for higher daily flow rates.

The following calculation illustrates sizing of a gas chlorination system:

Preliminary Design Calculations For A Gas Chlorination System:

Problem: Determine the capacity of a gas chlorination system to treat an average waterworks flow of 500,000 gal/day (1,893 m^3/day), peak flow of 1 million gal/day (3,786 m^3/day), and minimum flow of 250,000 gal/day (947 m^3/day).

Given: The water to be chlorinated has been determined to have a chlorine demand of 0.6 mg/L and State public health standards require 0.2 mg/L residual chlorine after chlorination.

A. total chlorine dosage = chlorine demand of water plus required chlorine residual = 0.6 mg/L + 0.2 mg/L = 0.8 mg/L.

B. average chlorine requirements = 0.5 mgd x 8.34 lb/gal x 0.8 mg/L = 2.34 lb (1.06 kg) chlorine/day.

C. maximum chlorine requirement = 1.0 mgd x 8.34 lb/gal x 0.8 mg/L = 6.67 lb (3.03 kg) chlorine/day.

D. minimum chlorine requirement = 0.25 mgd x 8.34 lb/gal x 0.8 mg/L = 1.67 lb (0.76 kg) chlorine/day.

Chlorination With Calcium Hypochlorite

Calcium hypochlorite is supplied as a white solid which is highly corrosive and gives off a strong chlorinous odor. It contains approximately 70% available chlorine, is readily soluble in water, and is available in granular, powdered, or tablet form. It is provided in 0.91, 2.27, 3.63, and 15.9 kg (2, 5, 8, 35 lb) cans and in 45.4, 136 and 363 kg (100, 300, and 800 lb) drums. The containers generally are resealable.

Calcium hypochlorite is hygroscopic (readily absorbs moisture), and reacts slowly with atmospheric moisture to form chlorine gas. Therefore, the shipping containers must be emptied completely or carefully resealed. It is not feasible to handle this material in bulk handling systems.

The contents of a calcium hypochlorite container are emptied into a mixing tank where it is readily and completely dissolved in water. The resulting highly corrosive solution is stored in and fed from a stock solution vessel constructed of corrosion-resistant materials such as plastic, ceramic glass, wood, or rubber-lined steel. Dosage of the solution at 1 or 2% available chlorine content is by diaphragm type, chemical feed/metering pumps.

The following calculations illustrate the sizing of a calcium hypochlorite system:

Preliminary Design Calculations For A Calcium Hypochlorite System:

Problem: How many pounds of 70% available calcium hypochlorite will be required to equal the output of the gas chlorination system previously described?

A. calcium hypochlorite required =

$$\frac{\text{pounds chlorine required/day}}{0.70 \text{ lb } Cl_2/\text{lb } Ca(OCl)_2} =$$

$$\text{lbs } Ca(OCl)_2/\text{day}$$

B. average $Ca(OCl)_2$ required =

$$\frac{2.34 \text{ lb chlorine required/day}}{0.70 \text{ lb } Cl_2/\text{lb } Ca(OCl)_2} =$$

$$3.34 \text{ lb } (1.52 \text{ kg})/\text{day}$$

C. maximum $Ca(OCl)_2$ required =

$$6.67/0.70 = 9.5 \text{ lb } (4.31 \text{ kg})/\text{day}$$

D. minimum $Ca(OCl)_2$ required =

$$1.67/0.70 = 2.38 \text{ lb } (1.08 \text{ kg})/\text{day}$$

Problem: How many pounds of dry calcium hypochlorite (70% available chlorine) are to be dissolved in 55 gallons of water to make up a 2% solution of available chlorine?

$$\frac{\text{lb water} \times (\%\text{ solution})/100\%}{(\%\text{ available } Cl_2)/100\%} =$$

$$\text{lbs } Ca(OCl)_2 \text{ required}$$

$$\frac{55 \text{ gal} \times 8.34 \text{ lbs/gal} \times (2\%/100\%)}{(70\%/100\%)} =$$

$$13 \text{ lbs } (5.90 \text{ kg}) \; Ca(OCl)_2$$

Calcium hypochlorite should be stored in its original, sealed shipping containers in a room specifically designed for chlorine chemicals, but separate from the chlorine handling and dissolving room. Provisions should be made for the rapid removal of the calcium hypochlorite from the storage room in case of fire. However, automatic sprinklers should not be provided, because of the evolution of chlorine gas which occurs when the solid calcium hypochlorite becomes wet.

Chlorination With Sodium Hypochlorite

Sodium hypochlorite, usually supplied in concentrations of 5 and 15% available chlorine, is commercially available only in liquid form. Supplied in this form, it is easier to handle than gaseous chlorine or calcium hypochlorite. However, sodium hypochlorite solutions will lose oxidizing (disinfecting) power during storage and should be stored in a cool, dark, dry area.

The material is supplied in glass or plastic bottles, carboys, or in lined drums ranging in size from 1.9 to 208 L (0.5 to 55 gal). Bulk shipment by tank truck also is a common form of transport. No more than a one-month supply of the chemical should be purchased to prevent loss of available chlorine.

The following calculations illustrate the sizing of a sodium hypochlorite solution system:

Preliminary Design Of Sodium Hypochlorite Solution System

Problem: How many gallons of 15% NaOCl solution will be required to equal the output of the gas chlorination system previously described?

A. Amount of available chlorine in sodium hypochlorite

% available chlorine	1	5	10	15
lbs available Cl_2 per gal	0.083	0.42	0.83	1.25

B. Amount of NaOCl required =

$$\frac{\text{lbs chlorine required/day}}{\text{lbs/gal available } Cl_2} = \text{gal NaOCl/day}$$

C. Average amount of NaOCl required =

$$\frac{\text{2.34 lb chlorine required/day}}{\text{1.25 lbs available } Cl_2\text{/gal}} = \text{1.87 gal (7.08 L)/day}$$

D. Maximum NaOCl solution required =

$$\frac{\text{6.67 lbs chlorine required/day}}{\text{1.25 lbs available } Cl_2\text{/gal}} = \text{5.34 gal (20.33 L)/day}$$

E. Minimum NaOCl solution required =

$$\frac{\text{1.67 lbs chlorine required/day}}{\text{1.25 lbs available } Cl_2\text{/gal}} = \text{1.34 gal (3.79 L)/day}$$

Problem: How many gallons of 15% NaOCl solution is to be mixed with water to make 55 gallons (208.33 L) of a 2% NaOCl solution?

$$\frac{\text{gal diluted solution x \% diluted solution}}{\text{\% concentrated solution}} = \text{gal concentrated solution}$$

$$\frac{\text{55 gal x 2\%}}{\text{15\%}} = \text{7.3 gal (27.65 L) gal concentrated NaOCl solution}$$

Sodium hypochlorite storage tanks are either plastic or rubber, or plastic lined. Storage tanks normally are located outdoors in temperate climates, but indoors in northern climates. Chemical feed pumps are used to add the chemical at its as-received strength.

CHLORINE DIOXIDE SYSTEMS DESIGN

This chemical is generated on-site, as a dilute aqueous solution, and in quantities as needed at the moment, to avoid storage of excesses. This aqueous solution then is metered at a rate paced and controlled by the flow rate of the water to be treated, so that a constant dosage of ClO_2 is added at all times, irrespective of the process water flow rate.

Table VIII provides a partial listing of chlorine dioxide equipment suppliers. Several different types of generation equipment are available which vary depending upon the supplier, but also upon the generation process chosen (gaseous chlorine versus sodium hypochlorite plus acid, or acid plus sodium chlorite solution, for example). Pertinent aspects of each type of chlorine dioxide generation equipment will be discussed in this sub-section.

All three of the chlorine dioxide generation procedures described in Section 3 are in general use in the United States at this time for application in small water treatment facilities. The three generation procedures are:

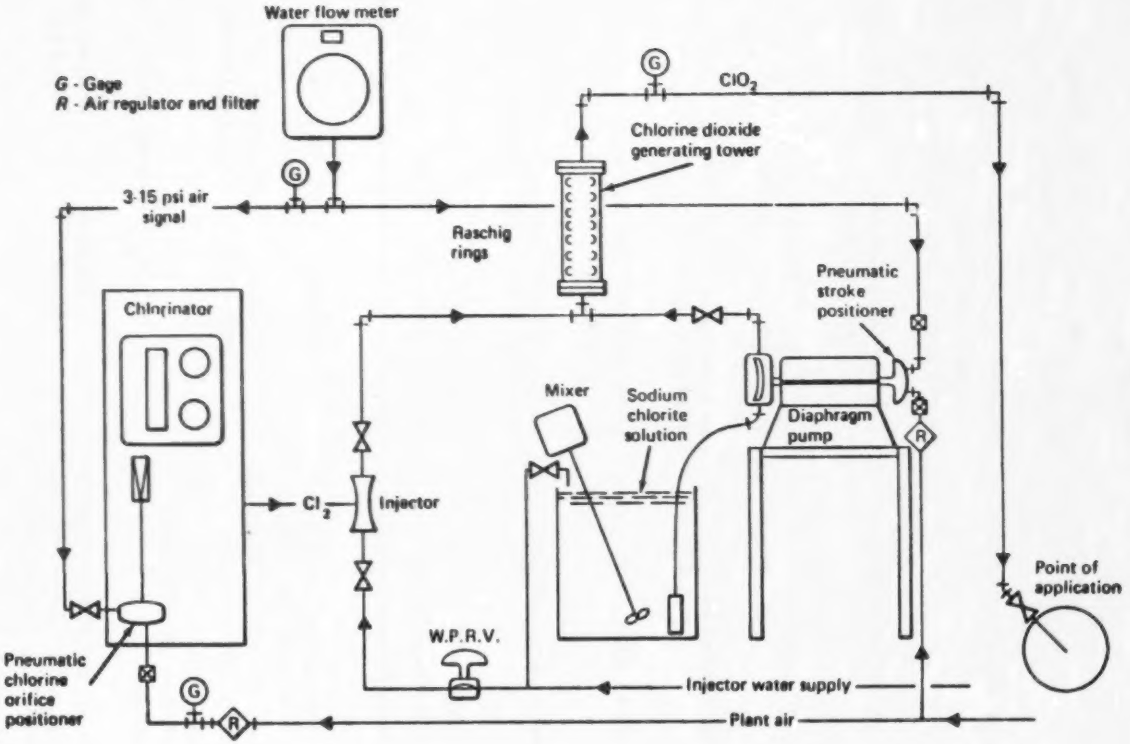
#1) chlorine gas + sodium chlorite solution
#2) sodium hypochlorite + sodium chlorite + acid
#3) sodium chlorite + mineral acid.

Chlorine plus sodium chlorite is the most commonly used chlorine dioxide production technique in the U.S. A schematic diagram of equipment marketed by Olin Water Services, which is designed to produce chlorine dioxide by this method is illustrated in Figure 15. However, the principles of operation are similar for equipment marketed by the other suppliers, except for CIFEC, whose equipment will be described later in this sub-section.

The gaseous chlorine procedure is particularly applicable when a gaseous chlorination system already exists at the water treatment plant. The reaction by which chlorine dioxide is generated is as follows:

$$\underset{\text{chlorine}}{Cl_2} + \underset{\text{sodium chlorite}}{2NaClO_2} \longrightarrow \underset{\text{chlorine dioxide}}{2ClO_2} + \underset{\text{sodium chloride}}{2NaCl}$$

This equation indicates that 71 lbs (26.48 kg) of chlorine mixed with a solution containing 181 lbs (67.5 kg) of 100% $NaClO_2$ will produce 135 lbs (50.36 kg) of chlorine dioxide. However, the ratio of reagents recommended by most suppliers of chlorine dioxide generating equipment and chemicals is 1:1 by weight. This means that more than double the stoichiometric amount of chlorine required by the equation above is utilized. This excess of chlorine over that required results in a faster reaction rate and insures a more complete reaction of


Water flow meter
G - Gage
R - Air regulator and filter
G
3-15 psi air signal
Raschig rings
G
ClO$_2$
Chlorine dioxide generating tower
Chlorinator
Cl$_2$
Injector
Mixer
Sodium chlorite solution
Pneumatic stroke positioner
Diaphragm pump
R
Point of application
W.P.R.V.
Injector water supply
Pneumatic chlorine orifice positioner
G
R
Plant air

Source: From HANDBOOK OF CHLORINATION, by George C. White (c) 1972 by Litton Educational Publishing, Inc. Reprinted by permission of Van Nostrand Reinhold Company.

Figure 15. Automatic Flow-Proportional Chlorine Dioxide System; Generation from Chlorine and Sodium Chlorite (31)

TABLE VIII

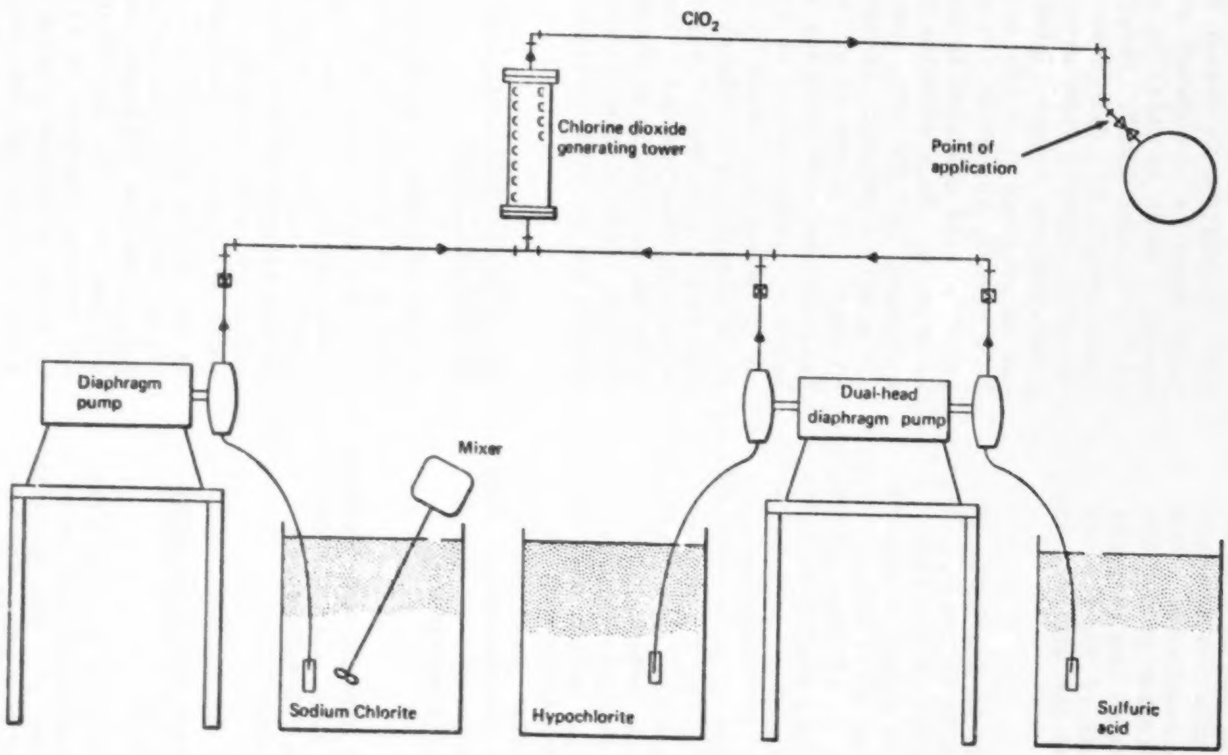
PARTIAL LISTING OF CHLORINE DIOXIDE EQUIPMENT SUPPLIERS

Name	Address
CIFEC	10 Ave de la Porte Molitor, F 7500, Paris, France
Fischer & Porter Co.	Environmental Division, County Line Road Warminster, PA 18974
International Dioxcide, Inc.	136 Central Avenue, Clark, NJ 07066
Olin Water Services Co.	120 Long Ridge Road Stamford, CT 06904
ProMinent Fluid Controls	503 Parkway View Drive, Pittsburgh, PA 15205
Rio Linda Chemical Co., Inc.	2444 Elkhorn Blvd., Rio Linda, CA 95673
Sherman Machine & Iron Works	26 E. Main Street, Oklahoma City, OK 73104
Wallace & Tiernan Division of Pennwalt Corp.	25 Main Street, Belleville, NJ 07109

chlorine with the chlorite ion. Because a large excess of chlorine is employed, chlorine dioxide solution prepared by this technique also will contain some free available chlorine, mostly as hypochlorous acid.

The production of chlorine dioxide using sodium hypochorite solution with sodium chlorite and sulfuric acid, as illustrated by Figure 16, is well suited to small systems. Dosage of each chemical can be derived from the following equation:

$$\underset{\text{sodium chlorate}}{2NaClO_2} + \underset{\text{sodium hypochlorite}}{NaOCl} + \underset{\text{sulfuric acid}}{H_2SO_4} \longrightarrow \underset{\text{chlorine dioxide}}{2ClO_2} + \underset{\text{sodium chloride}}{NaCl} + \underset{\text{sodium sulfate}}{\underline{Na_2SO_4}} + \underset{\text{water}}{H_2O}$$


ClO$_2$
Chlorine dioxide generating tower
Point of application
Diaphragm pump
Dual-head diaphragm pump
Mixer
Sodium Chlorite
Hypochlorite
Sulfuric acid

Source: From HANDBOOK OF CHLORINATION, by George C. White (c) 1972 by Litton Educational Publishing, Inc. Reprinted by permission of Van Nostrand Reinhold Company.

Figure 16. Equipment Arrangement for Generating Chlorine Dioxide from Hypochlorite and Acid (32)

In this system, all three reactants are in solution. Utilization of acid increases the conversion of chlorite ion to chlorine dioxide. Solution feed pumps of equal capacities can be used by adjusting the solution strength of each of the reactants. Thus, the chlorine dioxide production and addition rates can be paced by the flow rate of the product water and/or by its disinfectant demand.

Sodium chlorite is available in 55 gallon (208.33 L) drums, either as a solid (80% active $NaClO_2$) or as a solution containing 28 to 30% $NaClO_2$ (about 33% solids). If not used directly from the drum, sodium chlorite solution is stored in polyvinylchloride (PVC) or fiberglass tanks and transferred by means of PVC, rubber, or Tygon piping systems. Diaphragm pumps incorporating PVC as the material in contact with the solutions are used for pumping sodium chlorite solutions. Provision must be made for immediate washdown of any spills of the chemical. This precaution is generic to all chlorine dioxide generating systems.

Acid handling systems are designed and operated similarly to those of the sodium chlorite system described above.

The CIFEC System For Generating Chlorine Dioxide

A schematic diagram of this newer system is illustrated schematically in Figure 17. The equipment was developed in France, but has recently been installed at several U.S. water treatment plants. Because of its unique design features, this system is able to produce chlorine dioxide from gaseous chlorine, in high yield and containing little excess free chlorine.

Gaseous chlorine is passed into water which is circulated continuously in what is referred to as an "enrichment loop". Under these conditions, dissolved chlorine (hypochlorous acid) concentrations become higher than can be achieved in a single pass. As a result, the pH of the hypochlorous acid solution is lowered to below 4. This solution then is pumped into the ClO_2 reactor along with a solution of sodium chlorite. When the pH of the hypochlorous acid solution is below 4, conversion of chlorite ion to chlorine dioxide is claimed to be significantly higher than the single pass method employing elemental chlorine gas. Therefore, chlorine dioxide is produced which is free of significant quantities of free chlorine.

Rio Linda Chemical Chlorine Dioxide Generator

Figure 18 shows a schematic diagram of a newer acid/chlorite ClO_2 generator marketed by Rio Linda Chemical Co., Inc. Chlorine dioxide is generated by addition of dilute hydrochloric acid to sodium chlorite solution. The novel principle of this generator is the mixing of acid with concentrated sodium chlorite solution before the two solutions reach the reactor. The two solutions are brought together in an eductor by means of vacuum created by water flow through the eductor. Such a system eliminates a pump and allows the system to occupy a smaller space.

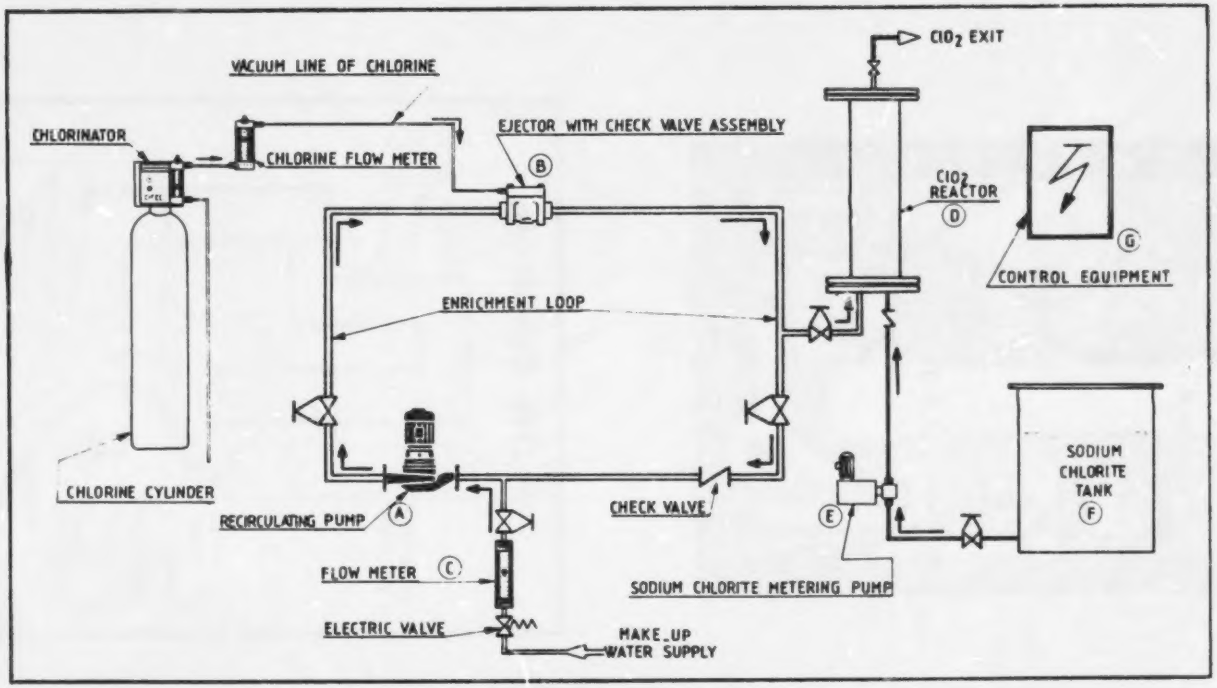
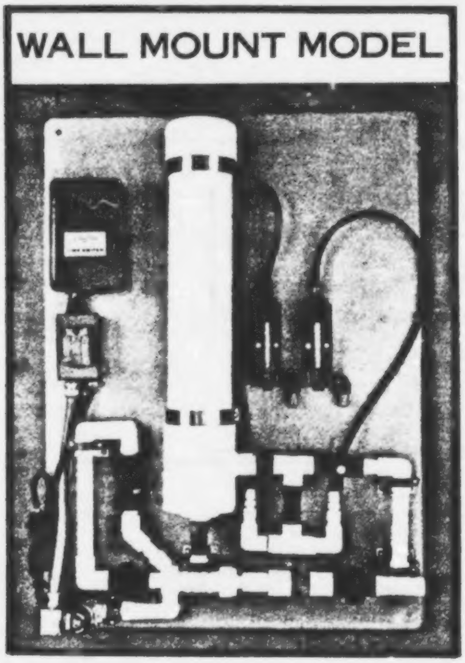

VACUUM LINE OF CHLORINE
CHLORINATOR
CHLORINE FLOW METER
EJECTOR WITH CHECK VALVE ASSEMBLY
B
ClO_2 EXIT
ClO_2 REACTOR
D
G
CONTROL EQUIPMENT
ENRICHMENT LOOP
CHLORINE CYLINDER
RECIRCULATING PUMP
A
CHECK VALVE
E
SODIUM CHLORITE TANK
F
FLOW METER
C
SODIUM CHLORITE METERING PUMP
ELECTRIC VALVE
MAKE_UP WATER SUPPLY

Figure 17. CIFEC Chlorine Dioxide System
(Courtesy CIFEC, Paris, France)


WALL MOUNT MODEL

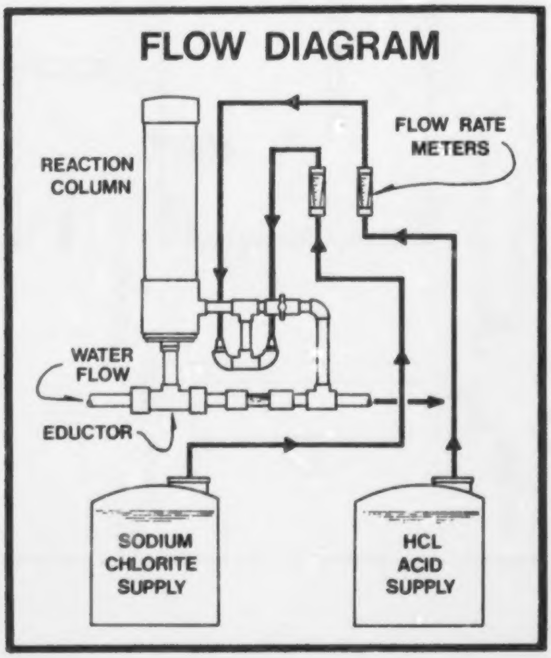

FLOW DIAGRAM
REACTION COLUMN
FLOW RATE METERS
WATER FLOW
EDUCTOR
SODIUM CHLORITE SUPPLY
HCL ACID SUPPLY

Figure 18. Rio Linda Chemical Company, Inc. Acid/$NaClO_2$ ClO_2 Generator

Miscellaneous Comments

Because several types of chlorine dioxide generation equipment are available, as well as three processes for its production, it is considered inappropriate to attempt to provide detailed instructions in this document for preparation of chemical solutions and feed rates of solutions. However, the small utility choosing to install chlorine dioxide generating equipment can have confidence that each equipment vendor will provide detailed recipes for preparing and metering the appropriate solutions to his chlorine dioxide reactor so as to produce an aqueous solution of chlorine dioxide of known and constant concentration for addition to the plant process water.

A final point to be noted is that the currently recommended maximum dosage level of 1 mg/L of chlorine dioxide means that a water supply system processing 0.5 mgd (1,893 m^3/day) would require a maximum ClO_2 production rate of only 4 lbs (1.82 kg)/day. Smaller systems would require even less ClO_2. At such low dosage levels, two of the three vendors of chlorine dioxide generating equipment contacted recommend that their units be operated intermittently, collecting ClO_2 solution in an enclosed holding tank for metering into the water being processed. This is because at the low flow rates of reactant solutions, mixing is less efficient in the ClO_2 reactor. As a consequence, conversion of chlorite ion to chlorine dioxide is less efficient.

CHLORAMINATION SYSTEM DESIGN

Ammonia is available as a gas (NH_3), as a 29% water solution (aqua ammonia), or in powdered form as ammonium sulfate, $(NH_4)_2SO_4$. Gaseous ammonia is supplied in 150-pound (68.1 kg) cylinders, similar to gaseous chlorine. Aqua ammonia is supplied in 55 gallon (208.33 L) drums. Ammonium sulfate is provided in 100-pound (45.4 kg) bags (98% pure, 25% available ammonia).

Gaseous ammonia normally is added to the treated water using systems and equipment similar to those used for handling gaseous chlorine. Aqua ammonia and ammonium sulfate solutions are handled using systems and equipment similar to those for sodium hypochlorite and calcium hypochlorite solutions, respectively. Aqua ammonia is basic, but is non-corrosive.

Sizing of the treatment facility would take into consideration the intended 3:1 chlorine:ammonia ratio.

A 25 to 30% solution of ammonium sulfate in water is prepared in a plastic or fiberglass container and added to the water by means of a chemical metering pump. Solutions of ammonium sulfate are stable, but are acidic, and therefore can be corrosive to some metals. Materials which will withstand dilute sulfuric acid also will easily resist any possible corrosion effects of dilute ammonium sulfate solutions.

OZONE DISINFECTION SYSTEM DESIGN

Ozone also is generated on-site, on an as-needed basis, and must be applied to the liquid stream as it is generated. Although ozone is generated from oxygen or air by custom designed units in major water and wastewater treatment plants throughout the world, units for small water treatment plants of the size discussed in this document normally are supplied in the form of pre-engineered, skid-mounted units. Such a unit is illustrated by Figures 19 and 20, and employs air as the sole feed gas because of the lower costs at small volumes of ozone required.

Components Of Ozone Generation Systems

Figure 21 illustrates the four basic components of an ozonation system which employs ambient air as the generator feed gas. The essential components include air preparation, electrical power supply, the ozone generator, and the ozone contacting apparatus (including destruction of excess ozone).

Air Preparation

Ambient air must be dried to a maximum -60°C dew point (a unit of moisture content of air). Even drier gas is preferable (lower than -60°C). Figure 22 illustrates the common type of air preparation system used for skid mounted units. This subprocess must be designed conservatively, especially for warm humid climates. Use of air having a dew point higher than -60°C will lower ozone production, foul the ozone production (dielectric) tubes, and increase corrosion problems in the generator unit and downstream as well.

Electrical Power Supply

Supply line voltage (220/440 V), or frequency in some cases, is varied to control the amount of ozone being generated and its rate of generation. Because these two parameters are varied in many ozone generating systems, the electrical power subunit can represent a proprietary product of the ozonation system supplier. As a result, the electrical power system must be specified as an integral power supply system specifically designed for the ozone generator to be supplied. In other words, the power system should be designed for and purchased from the ozone generating system supplier.

Ozone Generator

The most common commercially available ozone generators can be classified as follows:

- o horizontal tube; one electrode water-cooled;
- o vertical tube; one electrode water-cooled;
- o vertical tube; both electrodes cooled;
- o plate; water- or air-cooled.

The operating conditions of these ozone generators can be subdivided as follows:

- o low frequency (60 Hz), high voltage (>20,000V);
- o medium frequency (600 Hz), medium voltage (<20,000V);
- o high frequency (>1,000 Hz), low voltage (<10,000V).

Currently, low frequency, high voltage units are most common, but recent developments in electronic circuitry are resulting in

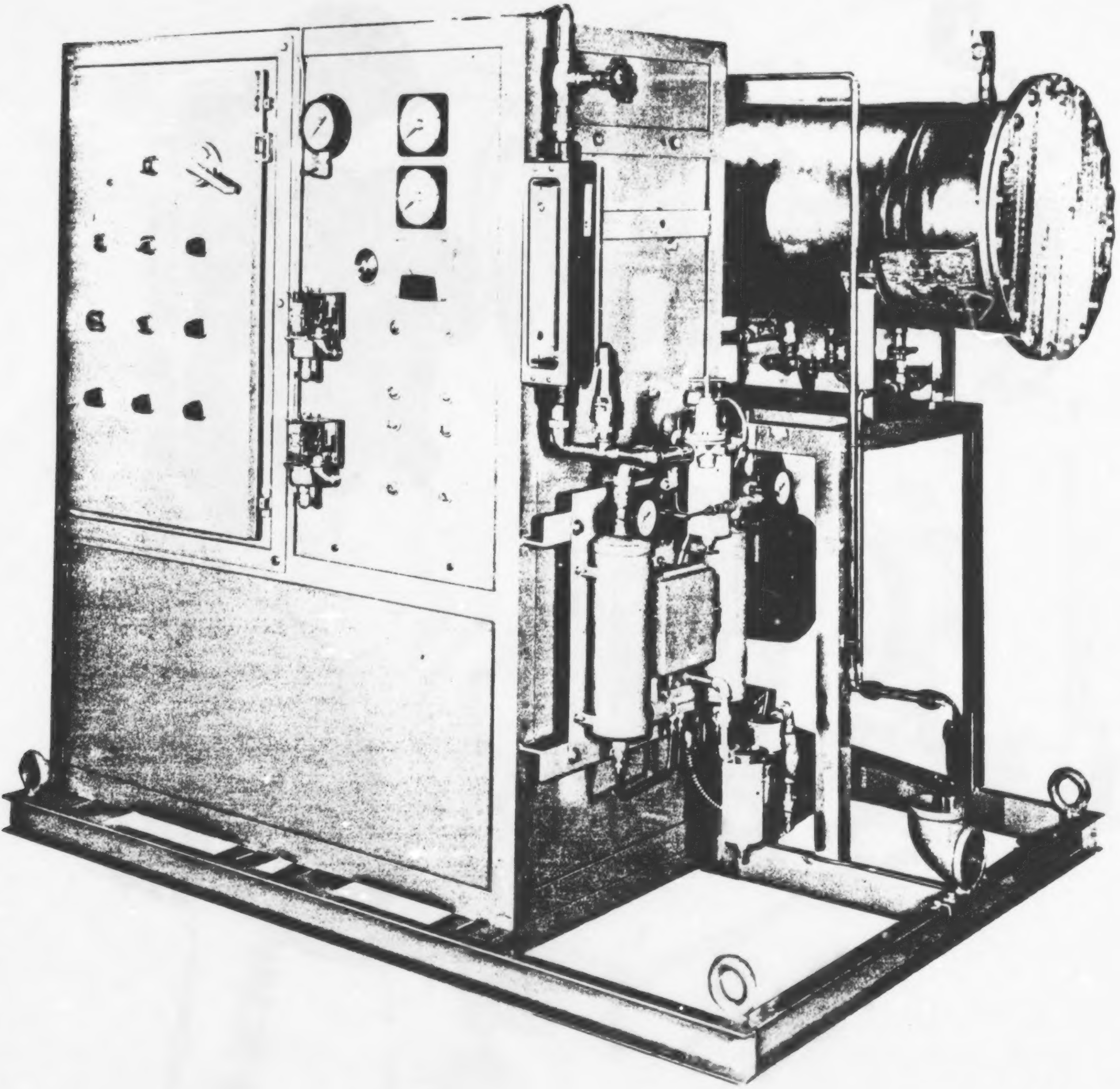


Figure 19. Preengineered, Skid-Mounted Ozone Generation System (Courtesy, Welsback Corporation, Palo, Alto, CA)

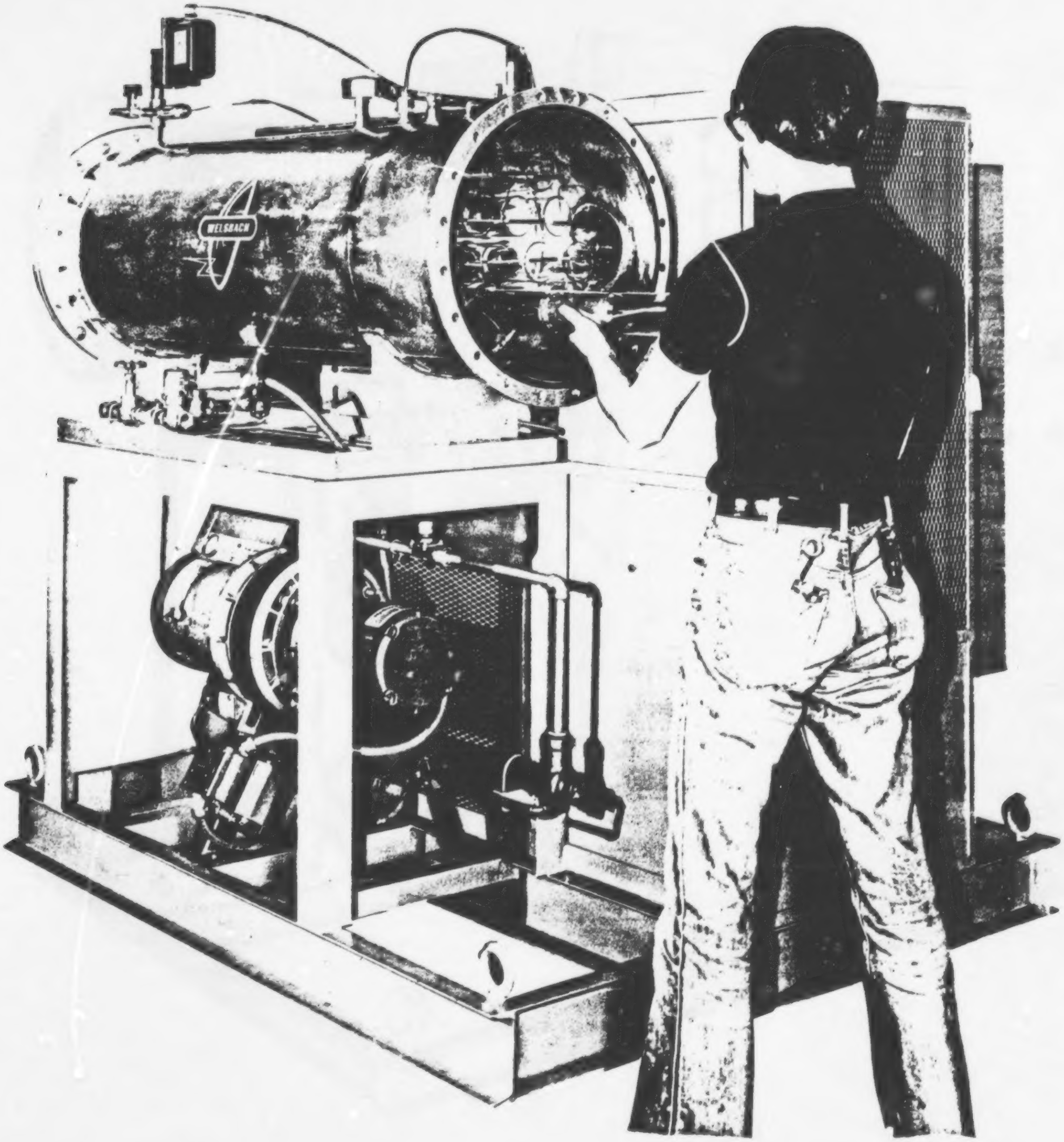


Figure 20. Different View of Skid-Mounted Ozone Generation System (Courtesy Welsback, Corporation, Palo Alto, CA)

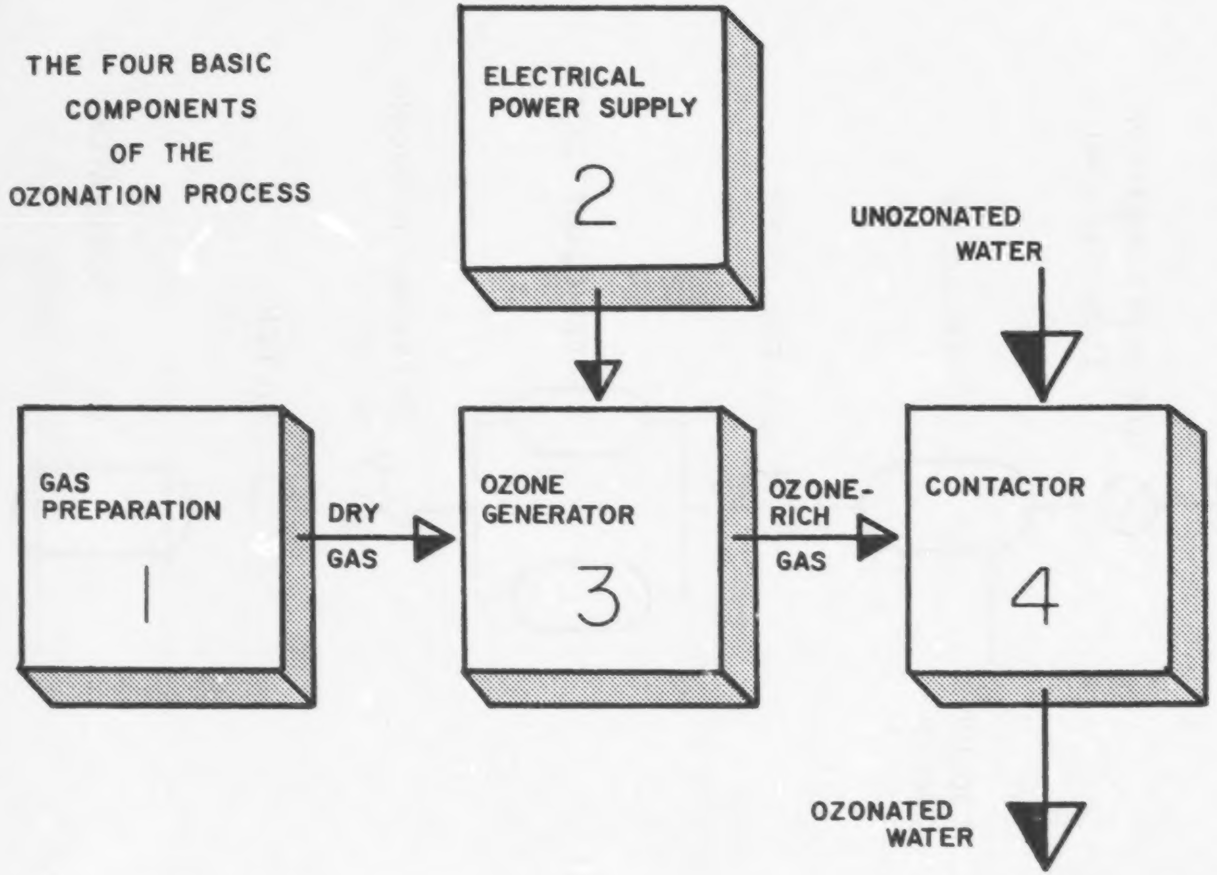

THE FOUR BASIC COMPONENTS OF THE OZONATION PROCESS
ELECTRICAL POWER SUPPLY
2
UNOZONATED WATER
GAS PREPARATION
1
DRY GAS
OZONE GENERATOR
3
OZONE-RICH GAS
CONTACTOR
4
OZONATED WATER

Figure 21. The Four Basic Components of an Ozonation System (33)

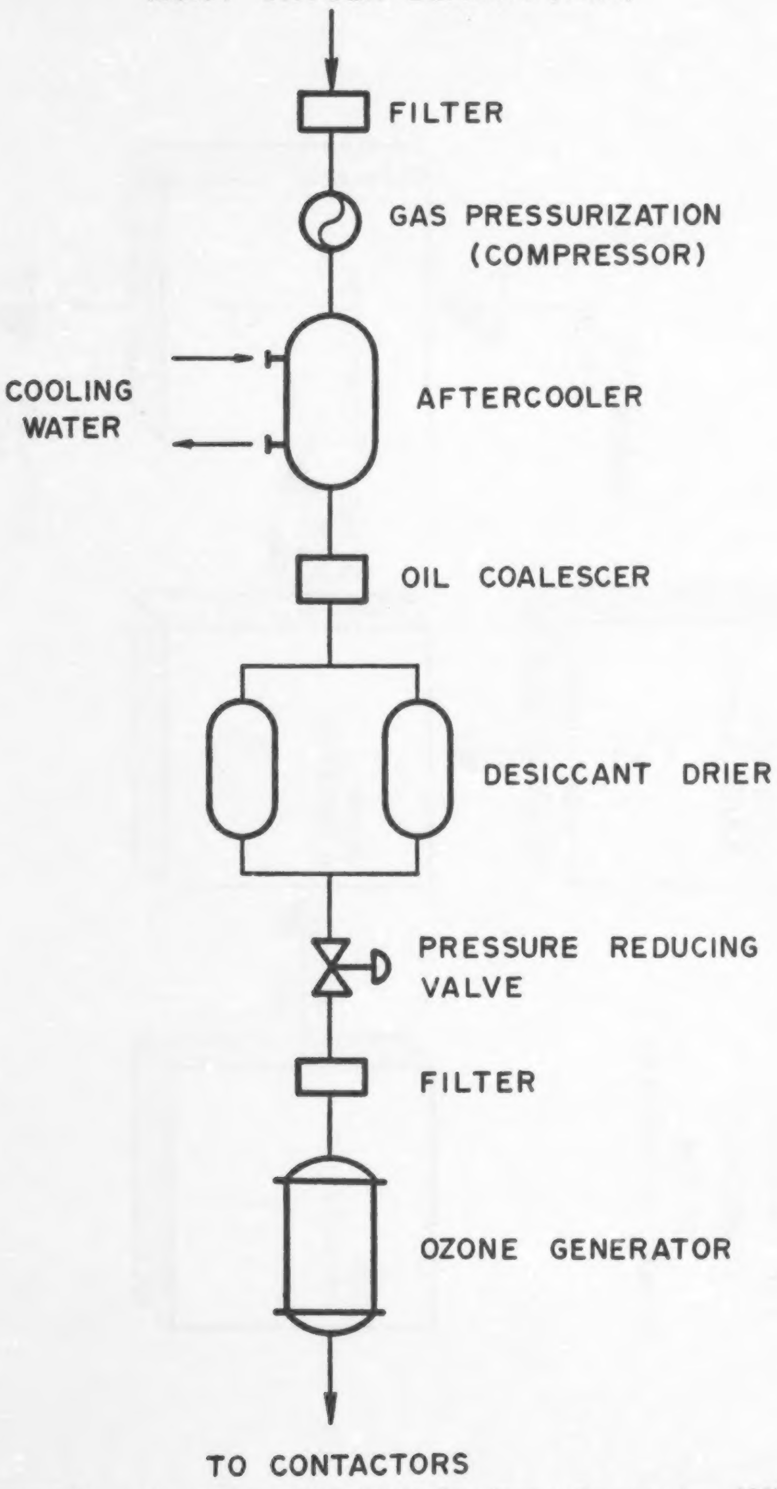

MOIST OXYGEN BEARING (AIR)
FILTER
GAS PRESSURIZATION (COMPRESSOR)
COOLING WATER
AFTERCOOLER
OIL COALESCER
DESICCANT DRIER
PRESSURE REDUCING VALVE
FILTER
OZONE GENERATOR
TO CONTACTORS

Figure 22. Air Preparation Unit for Ozone Generation (33)

higher frequency units (and lower voltages) being used.

Ozone Contacting (or Diffusion

Ozone is a gas, at ordinary temperatures and pressures, which is generated in concentrations of about 1% ozone plus 99% dried air by most available generators at the most efficient expenditure of electrical energy. It is not highly soluble in water (about 10 times more than oxygen as a rule of thumb), and must be brought rapidly into intimate contact with the water flow to make most efficient use of this disinfectant.

The following types of ozone contactors may be used for transferring ozone gas into the water to be treated. Each of these has advantages and disadvantages which have been discussed at length by Masschelein (34):

- o spray towers
- o packed beds
- o turbine mixers
- o injectors
- o porous diffusers

The required contact time will depend upon whether the specific application of ozone is dependent on the rate at which gaseous ozone dissolves in the water (ozone mass transfer dependent) or on the chemical reaction rate. Disinfection is a mass transfer dependent process, whereas oxidation of organic chemicals can be limited by the mass transfer rate or by the chemical reaction rate.

The most commonly used contactor for ozone disinfection in the production of drinking water is the multiple stage chamber using porous plate or porous tube diffusers, as illustrated by Figure 23.

Destruction Of Excess Ozone

At least 90% transfer of ozone from the gas exiting the generator into the water being treated is reasonable to expect by proper contactor design. However, the gases vented from the contactor (called contactor off-gases) still contain sufficient ozone to present possible hazards to plant personnel, nearby residents, and the immediate environment. Therefore, treatment of off-gas from the ozone contactor must be provided for in the design to reduce the ozone concentration to less than 0.1 ppm (by volume). This is the time-weighted average (over 8 hours) maximum allowable exposure limit currently set by the Occupational Safety and Health Administration for exposure of workers. This can be achieved by a number of methods which include the following:

- o dilution by prevailing winds or supplemental air;
- o passage through wet granular activated carbon;
- o thermal (heating);
- o catalytic thermal destruction;
- o recycling to other process stages.

The most favored procedure currently is passing the heated off-gases through a chamber containing a proprietary catalyst which reconverts the ozone to oxygen. The so-treated off-gas then may be vented safely to the atmosphere.

Ozone contactor off-gases are treated in this manner, rather than drying and recirculating through the ozone generator

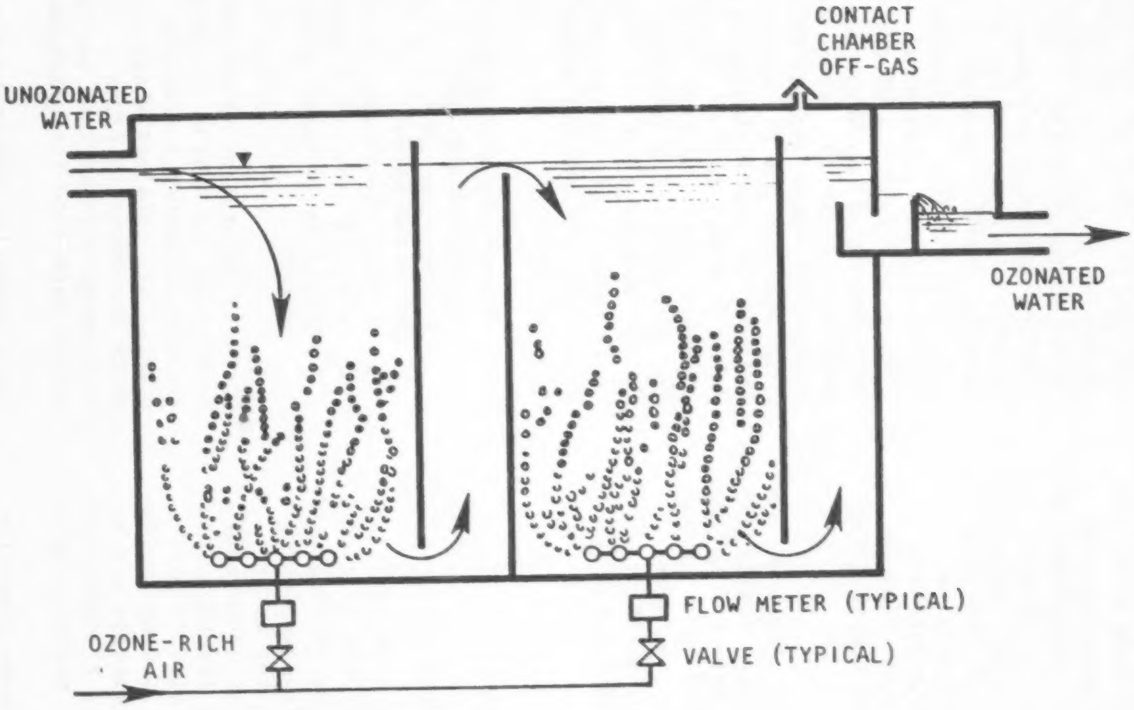

UNOZONATED WATER
CONTACT CHAMBER OFF-GAS
OZONATED WATER
FLOW METER (TYPICAL)
VALVE (TYPICAL)
OZONE-RICH AIR

Figure 23. Two-Compartment Ozone Contactor Using Porous Diffusers (Reference 24, p. 120)

because of economics. It is more cost-effective to dry ambient air than to dry the wet air exiting the ozone contactor.

Other Ozone Design Considerations

Materials Of Construction

Care must be taken in selecting materials of construction for those portions of the ozonation system in direct contact with either "dry" (before the contactor) or "wet" (after the contactor) ozone-containing gas. While reinforced concrete is an appropriate material for ozone contactors, the ozone-containing gas piping system should be 304 L and 316 L stainless steel for dry and wet services, respectively.

Monitoring Of The Ozonation System

Equipment should be provided to monitor the operation of the components of the system. The minimum degree of instrumentation, all of which can be provided by the ozone equipment supplier as part of the package units, is as follows:

- Gas pressure and temperature devices at key points in the air preparation system. Simple pressure gauges and mercury thermometers will suffice.
- Continuous monitoring of the dew point measuring device to determine the moisture content of the dried air feed gas to the generator. High dewpoint indications should be designed to sound an alarm and shut down the generator. Equipment for calibration of the dew point monitor should be provided as well.
- Means of measuring inlet and discharge temperatures of the ozone generator coolant medium (water and/or oil) is required, as is a means of determining whether the coolant is actually flowing through the generator. An automatic system shutdown should be provided if coolant flow is interrupted or if its discharge pressure exceeds specified limits.
- A means of measuring flow rate, temperature, pressure, and ozone concentration of the ozone-containing gas discharged from the ozone generator is required to determine the ozone production rate.
- A means of measuring the power input to the ozone generator is required.

Supplier's Obligations

The purchase order should stipulate that the supplier of the ozonation system is responsible for the supply, installation, initial checkover, startup, and operator training.

Maintenance Service Contract

The utility should consider entering into a maintenance service contract for the first two years of operation of the ozonation system. At the end of this period, the need for the service contract should be reevaluated versus the capability of plant personnel to provide the same services.

Table IX contains a listing of the major suppliers of ozone generation equipment in the United States. Each of these supplies the total ozone generation system, including electrical power supply, air preparation equipment, contacting apparatus, and contactor off-gas destruction device.

ULTRAVIOLET RADIATION SYSTEMS DESIGN

Utraviolet (UV) radiation is generated by means of special lamps which emit radiation at specific wavelengths. The majority of available UV generators are designed to operate using UV lamps which emit light at 254 nanometers (nm). At this wavelength, small amounts of ozo also are produced in the air surrounding the lamp itself.

Generation systems are enclosed systems which contain a varying number of UV bulbs, depending upon the size of the equipment. In turn, the size of the equipment required depends upon the volume of water to be disinfected. UV disinfection can be effective with equipment operating in ambient air and in water at temperatures in the range of 40 to 110°F. Therefore, UV generating units can be housed in small metal utility buildings. Should either the ambient air or water temperature be substantially outside this temperature range, heating or cooling packages are available from UV equipment suppliers to maintain the proper system operation.

Figure 13 (Section 3) is a schematic diagram of ultraviolet disinfection equipment as it is used for the disinfection of water.

UV generating units designed to disinfect 500,000 gpd (1,893 m^3/day) of water will occupy a floor space of about 40 square feet. Since UV systems are completely electrical, and operate satisfactorily with a 110V power supply, no special safety systems are required, except to remember not to open the UV unit during operation because of the hazards of eye exposure.

Water to be disinfected is piped into the UV generating unit where it flows past and/or around the UV lamps. The exact configuration of the lamps depends upon the design of the specific commercial unit. In any case, it should be realized that the UV generating lamps are submerged in the water being disinfected. Because of this, films of dissolved or suspended materials contained in the water can build up on the surface of the lamps. These films should be wiped off from time to time. Many units can be supplied with O-rings mounted around the lamp; these can be moved over the surface of the lamp from time to time to clean it.

The frequency with which the UV generating lamp bulbs require cleaning depends upon the quality of the water at the time it enters the UV disinfection unit. As stated earlier in this document, it is desirable to provide water that is as clean as practicable to receive any disinfectant, and this holds true for disinfection via ultraviolet radiation.

TABLE IX

U.S. OZONATION SYSTEMS SUPPLIERS

Name	Address
Envirotech Eimco Process Machinery	P.O. Box 300, Salt Lake City, UT 84110
Emery Industries, Inc.	4900 Este Avenue, Cincinnati, OH 45232
Griffin Technics Corporation	66 Route 46, Lodi, NJ 07644
Howe Baker Engineers, Inc.	3102 E. 5th St., Box 956, Tyler, TX 75710
Lotepro Corporation	1140 Avenue of the Americas, New York, NY 10036
Ozone Research & Equipment Corporation	3840 North 40th Avenue, Phoenix, AZ 85019
PCI Ozone Corp.	One Fairfield Crescent, West Caldwell, NJ 07006
U.S. Ozonair Corp.	464 Cabot Rd., South San Francisco, CA 94080
Welsbach Ozone Systems Corp. (Polymetrics Corp.)	1005 Timothy Drive, San Jose, CA 95133

During use, the ceramic housing of the bulbs through which UV radiation passes solarizes (i.e., crystalline forces in the ceramic change, and the material becomes cloudy), and the intensity of radiation passed into the water gradually decreases. The average lifetime of continuously operating UV lamps is only six to 12 months. However, changing lamps is no more difficult than changing a fluorescent light bulb.

UV generating units are easy to install, requiring only two plumbing connections (water in and water out) and one electrical connection (110V). In addition, maintenance requirements are low.

Table X contains a partial listing of suppliers of UV generating equipment.

SAFETY PROVISIONS FOR WORKING WITH DISINFECTANTS

Safety considerations must be paramount when designing disinfection systems. The chemicals discussed in this document can be hazardous if provisions for

TABLE X

MAJOR SUPPLIERS OF ULTRAVIOLET RADIATION EQUIPMENT

Name	Address
Aquafine Corporation	25230 Stanford Avenue West Valencia, CA 91355
Atlantic Ultraviolet Corp.	24-10 40th Avenue Long Island City, NY 11101
Jamlar Management Corp.	172 Riverside Drive N. Vancouver V7H 1T9, Canada
Katadyn-USA, Inc.	12219 St. James Road Potomac, MD 20854
Koala Manufacturing Co.	312 Roma Jean Parkway Streamwood, IL 60103
Port Star Industries, Inc.	375 N. Broadway, Suite 201 Jericho, NY 11753
Pure Water Systems	4 Edison Place Fairfield, NJ 07006
Refco Purification Systems, Inc.	P.O. Box 2356, Dept. H. San Leandro, CA 94577
Trojan Environmental Products	845 Consortium Court London, Ontario N6E 2S8, Canada
Ultra Dynamics Corp.	1636 10th Street Santa Monica, CA 90404
Ultraviolet Technology Inc.	1355 Descanso Avenue San Marcos, CA 92069
UV Purification Systems	111 Business Park Drive Armonk, NY 10504

emergency situations are not provided in the initial system designs. Such provisions must include:

- monitoring equipment;
- emergency breathing apparatus (preferably self-contained);
- protective clothing;
- eye protection:
- safety shower and eye wash;
- room ventilation;
- access doors;
- repair kits.

In addition, the following measures should be designed into the disinfection facility:

- All doors should open outward and be equipped with panic hardware which will eliminate the need for operation of a door knob or latch to open the door;

- A minimum of two self-contained breathing apparatus units suitable for chlorine service, certified by the National Institute of Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA), should be provided in the vicinity of the disinfection facility, but not in the equipment or storage rooms.

- Activation of emergency ventilator systems of the disinfection facility should actuate visual and audible alarms to alert all employees when emergency situations develop.

- Continuous gas monitoring is recommended in enclosed spaces where gaseous chemicals (chlorine, ammonia, and ozone) are generated or are used. Table XI lists the physiological effects of these gases. Each gas has a characteristic sharp and pungent odor, which normally would be readily detected at lower than toxic levels by operating personnel. However, olfactory fatigue could reduce the sensitivity of workers to the chemicals, and therefore, monitoring equipment should be supplied and maintained.

  The gas monitoring equipment should be wired to initiate an alarm sequence, which may include horns, lights, and telephone signals. In the case of an ozonation facility, the monitor would sound an alarm at levels of 0.1 mg/m^3 (0.05 ppm), and shut down the generator and start up room purge blowers if the ozone level reaches 0.2 mg/m^3 (0.1 ppm).

- Emergency showers and eye washes should be provided immediately adjacent to, but outside of, the disinfection facility. Showers and eye washes should not be provided in calcium hypochlorite storage rooms, since this chemical generates chlorine gas when mixed with water.

- Emergency room ventilation should be provided for the gases involved in disinfection. Air exhausts should be provided at floor level for chlorine and ozone and at ceiling level for ammonia. The emergency ventilation systems should be wired for initiation by monitors of gas levels, as well as by

TABLE XI

PHYSIOLOGICAL EFFECTS OF CHLORINE, AMMONIA AND OZONE

Physiological Effect	Parts of Gas per Million Parts of Air (by volume)		
	Chlorine	Ammonia	Ozone*
Detectable Odor	3.5	50	0.01
Throat Irritation	15.1	400	1
Coughing	30.2	1,720	?
Dangerous in 30 to 60 minutes	40 to 60	2,500-4,500	50
Lethal	1,000	?	2,000-3,000

* for 10 minute exposure times

emergency switches installed inside and outside of the rooms.

- Emergency repair tools, equipment, and materials should be maintained immediately adjacent to the disinfection facility. For example, a Chlorine Institute Emergency Kit A for 150-lb (68.1 kg) chlorine cylinders should be provided if gaseous chlorine or ammonia is to be used.
- Hose bibbs, hoses, and floor drains should be provided throughout the facility, with the exception of the calcium hypochlorite storage room.

Further guidance in ensuring safety provisions in disinfection facilities is provided by standard design guides and reference materials (29,30, 35-38).

ASSOCIATED DESIGN CONSIDERATIONS

Bid Documents

The bid documents (plans and specifications) for the disinfection facility must clearly establish the utility's intent. Construction materials and construction quality must be established clearly in order to minimize conflicts which may arise during the construction period. The utility may wish a general contractor to handle all aspects of the work, or may serve as its own general contractor by dealing directly with individual trade (electrical, mechanical, masonry) contractors. In any case, the appropriate review agencies normally require the bid documents to bear the seal of a professional engineer licensed to practice in the utility's state.

Since the plans of the facility are the sole record of the project that normally is retained, every effort should be made to have the original design criteria recorded on the plans. This record should include:

- design flows;
- disinfectant dosages;
- roof loadings;
- heating and ventilating provisions.

There may be equipment incorporated into the disinfection system with which the utility personnel is unsure of its ability to service and maintain. For this equipment, the bid documents should require that the equipment vendor provide regular service and maintenance by the vendor's service technicians for a specific period of time. This approach would be particularly appropriate for unfamiliar controls or monitoring equipment and unfamiliar processes such as disinfection with chlorine dioxide, ozone or ultraviolet radiation.

Operation & Maintenance Manuals

The utility should require that operation and maintenance (O&M) manuals be prepared by the consultant or equipment vendor. The O&M manual should include the following information:

- the original design concepts;
- description of the facility as constructed, including construction photographs of buried components;
- normal operational procedures;
- emergency operational procedures;
- organized collection of vendors' literature;
- safety considerations and requirements;
- schematics with all valves numbered to correspond to detailed operational procedures;
- maintenance procedures.

A number of copies of the manual, which may consist of more than one volume, should be provided to assure that working and record copies remain available throughout the operational life of the facility. The components of the O&M manual should be keyed to a facility component numbering system, as illustrated by Table XII.

Startup Assistance and Training

These services should be required of both the consultant and the various equipment vendors. Frequently, this assistance and training is a joint effort between the engineer and vendor personnel. In any event, the original contract must ensure that these services are provided. The engineer normally is held responsible to coordinate the startup and training services, but it is the utility's ultimate responsibility to determine whether its needs have been adequately satisfied.

Followup Engineering Services

Representatives of the engineer and key process equipment vendors should be required to provide a specific amount of followup services during the first year of facility operation. This should constitute a minimum of one day of effort at the site by specific personnel classifications every three months for the first nine

TABLE XII

EXAMPLE OF A PARTIAL FUNCTIONAL NUMBERING SYSTEM FOR A WATER TREATMENT PLANT

Numbering Code	Equipment
100	Well Pump Station
101	Pump No. 1
102	Pump No. 2
103	Pump No. 3
104	Pump Station Ventilation Fan
105	Pump Station Unit Heater
200	Chemical Clarification
201	Clarfier Drive Motors
202	Sludge Pump
203	Lime Silo
204	Lime Slaker
205	Motor Control Center No. MCC 2
300	Filter Building
301	Pressure Filter No. 1
302	Pressure Filter No. 2
303	Pressure Filter No. 3
304	Pressure Filter No. 4
305	Backwash Pump
306	Backwash Pump
307	Motor Control Center No. MCC 3
308	Filter Building Unit Heater
400	High Head Pump Station
401	Pump No. 1
402	Pump No. 2
403	Pump No. 3
404	Motor Control Center No. MCC 4
405	Pump Station Unit Heater
500	Disinfection Building
501	Chlorinator No. 1
502	Chlorinator No. 2
503	Chlorinator Scale No. 1
504	Chlorinator Scale No. 2
505	Chlorine Storage Room Ventilator Fan
506	Chlorine Feed Room Ventilator Fan
507	Chlorine Storage Room Unit Heater
508	Chlorine Feed Room Unit Heater

months and the two days immediately prior to expiration of the warranty period.

The engineering services contract and the bid documents should ensure the following equipment, material, and information is provided prior to facility startup:

- safety equipment;
- special tools;
- process testing equipment;
- instrument calibration equipment;
- contract documents;
- vendors' literature;
- draft O&M manual.

The engineer should be required to provide the following information within three months of facility startup:

- record (as-built) drawings;
- final O&M manual;
- technical library on disinfection, such as AWWA manuals;
- copies of the project file, including correspondence, shop drawings, and payment records.

V. COST ESTIMATING PROCEDURES AND FUNDING SOURCES

This section provides a summary of the kinds of costs that are likely to be encountered in any water treatment facility construction project, and outlines a procedure to estimate costs associated with treatment for microorganism destruction. It also summarizes (in association with Appendix A) some estimated construction and operating cost projections which have been made for disinfection systems, explains how to update cost estimates, and provides an overview of potential funding sources for small water utilities.

COST ESTIMATING PROCEDURES

The total cost estimate for a water treatment facility generally is the sum of the costs associated with two major categories:

- construction costs
- operation and maintenance costs

Each of these major cost categories is composed of individual costs for a number of components. To arrive at a total cost estimate for a given facility, the component costs are evaluated, adjusted as necessary for site-specific considerations and inflation, then summed.

Costs can be expressed many ways: annual cost and cost per thousand gallons of water treated are two of the most common. The latter can be used directly to estimate the effect the project will have on the individual consumer's water bill. However, cost curves generally are most useful for comparing relative costs of the treatment alternatives and for approximating the general cost level to be expected for a proposed water treatment system.

Construction Costs

Whenever treatment costs are determined, whether from a published report or from a vendor's estimate, it is critically important to establish exactly what components and processes the cost estimate includes. Different cost estimates based on different basic assumptions (such as water quality) and different components (such as housing) have resulted in many misunderstandings in the past. In addition, if cost data are taken from a report, it is important to be sure they apply to the size category of your system. Once this has been ensured, cost comparisons between alternatives can be made using the process outlined above.

To illustrate this procedure, the cost information developed by the EPA Municipal Environmental Research Laboratory [presented in a four-volume series of reports entitled: Estimating Water Treatment Costs (EPA-600/2-79-162a,b,c, and d)] can be used. Volume 3 of this four-volume set (39) presents cost data and curves applicable to small water supply systems (2,500 gpd to 1 mgd) for 99 unit processes useful for removing contaminants covered by the NIPDWR. Some of these unit processes involve the use of disinfectants.

In this regard, other EPA-sponsored projects currently are in progress to refine and improve the accuracy of the cost data base. As these projects are completed, they should be consulted to obtain more accurate cost estimates.

The construction cost curves in Reference 39 were developed by using equipment cost data supplied by manufacturers, cost data from actual plant construction, published data, and using estimating techniques described in Richardson Engineering Services Process Plant Construction Estimating Standards, Mean's Building Construction Cost Data, and the Dodge Guide for Estimating Public Works Construction Costs. The construction cost curves then were checked and verified by an independent engineering consulting firm.

Although the cost data in Reference 39 are somewhat outdated and do not include cost curves for some of the most common disinfection processes, the method used to generate costs provides an outline of the items to consider when developing cost estimates. These include:

- Excavation and Site Work

  This category includes work related only to the applicable process and does not include any general sitework, such as sidewalks, roads, driveways, or landscaping, which should be itemized separately.

- Manufactured Equipment

  This category includes estimated purchase costs of pumps, drives, process equipment, specific purpose controls, and other items that are factory-made and sold with equipment.

- Concrete

  This category includes the delivered cost of ready-mix concrete and concrete-forming materials.

- Steel

  This category includes reinforcing steel for concrete and miscellaneous steel not included within the manufactured equipment category.

- Labor

  The labor associated with installing manufactured equipment, and piping and valves, constructing concrete forms, and placing concrete and reinforcing steel are included in this category.

- Pipe and Valves

  Cast iron pipe, steel pipe, valves, and fittings have been combined into a single category. The purchase price of pipe, valves, fittings, and associated support devices are included within this category.

- Electrical Equipment and Instrumentation

  The cost of process electrical equipment, wiring, and general instrumentation associated with the process equipment is included in this category.

- Housing

  In lieu of segregating building costs into several components, this category represents all material and labor costs associated with the building, including equipment for heating, ventilating, air conditioning, lighting, normal convenience outlets, and the slab and foundation.

To the subtotal for construction costs normally is added 15 percent for contingencies.

The total construction cost is obtained by adding to the above costs the cost of the following items:

Special sitework;
General contractor overhead and profit;
Engineering;
Interest;
Land;
Legal, fiscal, and administrative services.

These costs are not directly applicable to the costs for specific disinfection processes, but typically, will average between 30% and 35% of the total construction cost. The cost curves of Reference 39 do not include these items; they must be added on to arrive at a total cost estimate.

The costs given in Reference 39 are based on October 1978 dollars, and can be updated by using the Engineering News Record (ENR)* Construction Cost Index (CCI) or Building Cost Index (BCI).

The following formula can be used to update construction costs:

$$\text{Updated Cost} = \text{Cost from Curve} \times \frac{(\text{current ENR-CCI})}{(\text{ENR-CCI when costs were determined})}$$

The cost curves used in Reference 39 are based on October 1978 costs, when the ENR-CCI was 265.38. As of June 1982, the ENR-CCI was 352.92. Thus, to update the Reference 39 cost estimates to June 1982, they must be multiplied by the ratio of 352.92/265.38, which equals 1.33.

Note that this is the average of the 20-city construction cost index -- and that there is a wide variation between data of individual cities and regions of the U.S. For example, the August 1981 index varied from a low of 274 to a high of 360 among the 20 cities, about a 31 percent difference. As a result, updated cost figures using this adjustment may tend to overestimate or underestimate costs, depending upon construction costs in the locality of interest. More sophisticated cost estimating techniques are available, and are described in Reference 39.

Annualizing Construction Costs

To determine the true total yearly cost of owning, maintaining, and operating a disinfection system, all costs must be stated on an annualized basis. As shown later herein, O&M costs normally are stated on this basis. Capital costs can be annualized as a series of equal payments needed to recover the initial expenditure over the life of the project, plus interest costs.

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* Engineering News Record is a weekly McGraw-Hill publication which periodically summarizes updated Construction Cost (and other) Indices.

The size of the annual payment needed to recover the initial capital cost can be determined by multiplying the lump sum amount times a Capital Recovery Factor (CRF):

Annualized Construction Cost = Construction Cost x CRF

The CRF is a function of the interest rate "i" (cost of money) and the life of the system in years (n)(40):

$$CRF = i(1 + i)^n/[(1 + i)^n - 1]$$

Many finance handbooks provide tables of CRF values corresponding to various combinations of interest and financing period. Table XIII is an abbreviated example of this type of table, taken from Reference 40. The illustrative cost calculation example given below shows how this can be used to find the annual cost of a proposed system's capital cost based on the expected financing term and interest cost.

Operation and Maintenance Costs

To obtain a total operation and maintenance (O&M) cost, the individual costs for energy (process and building heating), maintenance material, and labor must be determined and summed.

Total operation and maintenance costs from a reference document or previous contractor's estimate can be updated and adjusted to local conditions by updating and adjusting the operation and maintenance cost components: energy, labor, and maintenance material.

Energy requirements generally are provided in kilowatts per year, and labor in hours per year. Cost curves are developed by multiplying these requirements by the costs of power and labor, respectively. To update such curves, the cost per year is multiplied by the ratio of current energy or labor costs divided by the respective unit cost used to develop the original curve. For example, assume an available energy cost curve was based on an energy cost of $0.03 per kilowatt-hour. If electricity now costs $0.05 per kilowatt-hour, the current annual energy cost for a given facility can be determined by multiplying the annual cost from the graph by the ratio of 0.05/0.03.

Likewise, maintenance material costs are related to the Producer Price Index (PPI) for Finished Goods. To update this component, the PPI at the time the original cost estimates were made must be known. Then the new annual cost is determined by multiplying the cost from the graph by the ratio of the new PPI divided by the PPI at the time the graph was prepared.

O&M Cost Basis And Assumptions

O&M costs also must be determined based on site-specific considerations, such as volume of water treated, energy costs, labor costs, and building heating requirements. O&M costs do not include the cost of chemicals; these must be added to the sum of annualized construction costs and O&M costs to arrive at total annual costs.

TABLE XIII

CAPITAL RECOVERY FACTORS FOR SOME COMBINATIONS OF INTEREST (i) AND FINANCING PERIOND (n)

n Years	6%	7%	8%	9%	10%	12%
5	0.237396	0.243891	0.240456	0.257092	0.263797	0.277410
10	0.135868	0.142378	0.149029	0.155820	0.162745	0.176984
15	0.102963	0.109795	0.116830	0.124059	0.131474	0.146824
20	0.087185	0.094393	0.101852	0.109546	0.117460	0.133879
25	0.078227	0.085811	0.093679	0.101806	0.110168	0.127500

The procedures outlined on the previous pages were used to develop the following illustrative cost example:

Example for Approximating Total Annual Costs for a Small Solution-Feed Chlorination System Using Chlorine Gas (Feed Capacity = 100 lbs/day)

Step 1: Calculate Cost Adjustment Factors as of the desired date (assume June 1982, for example).

A. Construction Cost Escalation Factor (CCEF)

$$\text{CCEF} = \frac{\text{Current ENR-CCI}}{\text{Base ENR-CCI}}$$

The cost curves of Reference 39 are based on October 1978 cost data when the ENR-CCI was 265.38. The June 1982 ENR-CCI was 352.92.

Therefore:

$$\text{CCEF} = \frac{352.92}{265.38} = 1.33$$

B. Maintenance Material Cost Escalation Factor (MMCEF)

$$\text{MMCEF} = \frac{\text{Current PPI}}{\text{Base Year PPI}}$$

The October 1978 U.S. Department of Commerce Producer Price Index (PPI) was 199.7. The June 1982 PPI was 299.4.

Therefore:

$$\text{MMCEF} = \frac{299.4}{199.7} = 1.50$$

Step 2: Determine Construction Costs

The Reference 39 construction cost for gaseous chlorine was $4,310, which included manufactured equipment, labor, pipe and valves, electrical housing (25 ft^2) and 15% of the total estimate for contingencies.

June 1982 construction cost x CCEF = $4,310 x 1.33 = $5,272

Step 3: Add 30% ($1,720) for special site work, general contractor overhead and profit, engineering, land, legal, fiscal and administrative services.

TOTAL CONSTRUCTION COSTS = $5,272 + $1,720 = $7,092

Step 4: Annualize Total Construction Costs

A. Assume loan conditions are:

interest @ 12%
loan period - 20 years

B. Determine CRF (see Table XIII)

CRF @ 12% for 20 years = 0.133879

C. Determine annual construction cost =

total construction costs x CRF:

$7,092 x 0.133879 = $949.47

Step 5: Determine Operation and Maintenance Costs

Reference 39 estimates that process energy (booster pump) requires 1,630 kWh/yr. At an energy cost of $0.07/kWh, the annual cost is:

1,630 kWh x $0.07/kWh = $114.10

Building energy (note that this is extremely site-specific) requires 2,560 kWh/yr. Thus the annual building cost =

2,560 kWh/yr x $0.07/kWh = $179.20

Maintenance material is estimated at $40/yr (1978 costs). Thus, 1982 costs =

$40 x MMCEF = $40 x 1.5 = $60.00/yr

Labor requirements are estimated at 183 hrs/yr. Assuming labor rates at $10.00/hr, then labor costs =

183 hrs/yr x $10.00/hr = $1,830/yr

Total O&M Costs = the sum of the above =	$ 114.10
	179.20
	60.00
	1,830.00
Total	$2,183.30

Step 6: Determine Chemical Costs

Chemical costs are discretely related to both the volume of water flow treated and to the dosage of chemical disinfectant applied. A small plant treating 250,000 gal/day (946,324 L/day) at an average applied chlorine dosage of 5 mg/L would use:

946,324 L/day x 5 mg/L = 4,731,620 mg chlorine/day

4,731,620 mg/day x 1 g/1,000 mg = 4,731.62 g chlorine/day

4,731.62 g/day x 1 lb/435.59 g = 10.43 lbs chlorine/day

10.43 lbs/day x 365 days/yr = 3,807 lbs of chlorine/yr

At an estimated cost of $0.47/lb (Washington, DC area price in early 1983), the annual cost for chlorine gas would be:

3,807 lbs/yr x $0.47/lb = $1,789/yr

Step 7: Determine Total Annual Cost

Total annual construction cost	=	$ 949.47
Annual operation & maintenance costs	=	2,183.30
Annual chemical costs	=	1,789.00
TOTAL ANNUAL COSTS	=	$4,921.77

Step 8: Determine Cost per 1,000 Gallons of Water Treated

Cost per thousand gallons treated can be determined by dividing the total annual cost by the total annual water production:

if 250,000 gallons of water are produced daily, then

250,000 gal/day x 365 days/yr =

91,250,000 gallons produced annually

Total annual cost per gallon =

$4,921.77/91,250,000 gal = $0.000053937/gal

$0.000053937/gal x 1,000 gal = $0.053937/1,000 gal, or

5.4¢/1,000 gallons of water treated

Because costs of equipment, labor, energy, and chemicals are subject to rapid change, the authors have determined more recent costs for the various methods of disinfecting drinking water supplies for small water treatment systems by obtaining vendor estimates (in mid-1982), rather than by relying upon ENR's Construction Cost Indices and attempting to update data developed from EPA's October 1978 values. This information, augmented by information in the earlier EPA report (Reference 39), where considered appropriate, is provided in Appendix A. Additional cost information obtained at several operating plants is provided in Section 7, CASE HISTORIES.

FUNDING SOURCES

The principal financing options open to small water systems for treatment process improvement can be categorized as follows:

- Self Financing
- Grant Programs
- Direct Loan Programs
- Loan Guarantee Programs
- Other Assistance Programs
  - Bond Banks
  - Research and Development
  - State Loan Programs
  - Shared Operator Costs With Other Utilities

These are discussed below.

Self-Financing

Water utilities process, deliver and charge consumers for potable water. In providing this service, they bear close resemblance to other businesses that provide products and services. Most larger utilities, publicly or privately owned, normally do not have problems in financing needed capital improvements, achieved either through increases in user fees or by floating bond issues (41). However, the financing needs for constructing and operating sufficiently sophisticated disinfection systems may strain the financial capabilities of small community water systems, either by requiring capital expenditures beyond their ability to finance, or by causing relatively large incremental increases in user charges. The latter course may incur substantial consumer resistance to the improvement program, a major impediment in the case of publicly owned systems. Very small systems may be particularly vulnerable to problems of this type.

The prime considerations for self-financing include the following (41):

- amount of revenues available for payment of interest costs;
- ratio of new treatment capital costs to existing assets;
- percent rate increase needed to finance and operate treatment;
- ratio of typical residential water bill to the community's median family income.

In competing for funds in the private capital markets, the larger utility is expected to have a debt service ratio (ratio of income less operating expenses to interest costs) of 1.3 and income at least twice that of interest charges. Private utilities must be showing a net profit, after taxes, of 10 to 13 percent. User fees should amount to less than 1.5 to 2.0 percent of median family income (41).

Smaller utilities may not be able to compete in the capital markets, but still may have the ability to raise money locally. Utility customers may be willing and able to put up the needed capital. Even so, the utility should have a debt service ratio of at least 1.0 so that interest and bond repayment schedules can be met.

Grant Programs

The principal financial assistance program available to small community water systems (public or private nonprofit) is operated by the Farmers Home Administration (FmHA) of the Department of Agriculture. FmHA can grant up to 75 percent of the cost for installation, repair or upgrading of community water systems that serve fewer than 10,000 people. The emphasis of this program, as its name implies, is on farmers and other rural residents.

Program aid priorities are as follows:

- public bodies and towns with emphasis to those serving 5,500 people or less;
- assistance in complying with the Safe Drinking Water Act;
- low income communities;
- systems proposing to merge and/or regionalize;
- state recommended projects;
- projects promoting water energy conservation.

FmHA can be contacted for further information at any one of 340 offices nationwide.

Direct Loan Programs

The Farmers Home Administration has a direct loan program with criteria similar to those used in their grant program. The loan can be for 100 percent of the project cost.

Loan Guarantee Programs

The Farmers Home Administration (FmHA) can provide backing for privately placed loans through its Business and Industry Loan Program. This is available to public or private organizations, particularly those located in rural areas and serving fewer than 50,000 persons. Loan guarantees range up to 90 percent of face value.

Other Forms of Assistance

Other methods of reducing financing and/or operating costs include the following:

Bond Banks

Several states have central bond banks that assist localities in the mechanics of bond financing. By aggregating small bonds into larger ones, interest costs may be reduced and bond placement enhanced.

Research and Development

The U.S. Environmental Protection Agency (EPA) has funded pilot plant demonstration projects for water and wastewater systems using uncommon technologies. Pilot plant studies at McFarland, California, were carried out as part of an EPA research project.

State Loan Programs

Several states provide direct loans for construction of public water and sewer projects. States with either loan programs or cost-sharing programs include Pennsylvania, New Jersey, Massachusetts, and Washington.

Shared Operator Costs With Other Utilities

Operation and maintenance of a single small water system does not require a full-time person; hence, operator costs could be divided up between two or more nearby utilities where travel distance permits. Regionalization is one approach to shared operating expenses.

VI. OPERATION AND MAINTENANCE

INTRODUCTION

Ultimately, on a day to day basis, the operator is responsible for providing clean, safe drinking water in a cost-effective manner. Proper operation and maintenance of disinfection facilities is essential to protect the health of water utility consumers. Adequate personnel, training, equipment, tools, and material must be provided to operate and maintain the disinfection system. Regardless of the quality of the physical plant, a water treatment facility is only as good as the people who run it. Inadequately skilled or trained operators can cost the utility many times their annual salaries in equipment damage and excessive O&M costs. Points to remember when starting and staffing new plants include the following:

- Hire and expect to pay skilled operators. The provision of safe drinking water is a highly responsible profession. Senior operators/-managers should have appropriate training in sanitation, process control and management.

- Hire the plant staff sufficiently in advance of initiating operation so that a startup training program can be carried out. Include training of the staff in equipment purchase contracts, and request the services of factory experts for equipment break-in and shakedown. Have engineers give the operators specific training in process operation and control. Enlist the aid of local and state sanitarians to train the staff in the health aspects of plant operation, including mandated sampling, monitoring, and reporting.

- Support a program of continuing education for the staff. Include in the utility budget the costs of membership of the utility -- as well as of the operators -- in professional organizations. Provide funding and time off for staff participation in continuing education seminars at local/state universities and health departments. Subscribe to trade journals and publications to foster a high-quality professionalism and esprit in the staff.

OPERATION AND MAINTENANCE PRACTICES

Good O&M practices include the following items:

- Encouragement of good operator attitudes and skills,
- Provision of up to date manuals, equipment, and safety devices,
- Appropriate monitoring programs,
- An effective preventive maintenance program,
- An understanding of emergency procedures,
- Routine use of good sanitary practices,
- Routine use of effective safety procedures,
- Compliance with the requirements of the NIPDWR.

Encouragement of Good Operator Attitudes and Skills

Operation of small disinfection systems does not require unusual operator skills. However, the operator must have a high level of awareness of the importance of drinking water disinfection and must be dedicated to continuous proper operation of the equipment. Assigned personnel should have sufficient comprehension levels to enable them to read and understand:

- basic literature on drinking water disinfection;
- equipment vendor manuals;
- process diagrams;
- electrical diagrams; and
- other literature associated with the process.

Operators should be reasonably expert in performing simple plumbing, electrical, and analytical tasks and should understand the operation and repair of valves, water meters, pumps, and controls. Disinfection personnel must be capable of carrying out regular sampling and monitoring programs and be able to calibrate and use residual disinfectant analyzers.

The skills of the utility staff may have to be supplemented by means of service contracts with disinfection equipment vendors. These may be required for work which requires equipment and skills beyond those maintained by the utility. Examples of such work include cleaning and adjustment of chlorinators, ozone generators, and instruments. Availability of such services will have been a major factor in the initial selection and specification of the disinfection system components.

Operating personnel should be given the opportunity to participate in design decisions and to observe construction progress. Within the constraints of project protocol and harmony, personnel should observe the installation activities of the equipment vendors' technicians. Appropriate utility personnel must take the maximum benefit from the vendors' training required (and paid for) as part of the construction contract. The construction contractor should not be released from his training obligation until the utility personnel have certified that they have been adequately trained in the use of disinfection facilities and associated equipment. It may be possible to maintain a permanent record of the vendor training program by means of tape recordings or video recording equipment.

The design engineer has a contractual or implied obligation to familiarize the utility's operation and maintenance personnel with the features of the disinfection system. These efforts by the engineer may include formal classroom training or may be limited to "hands-on" training in the field. In either case, all appropriate utility personnel should be required to attend such training programs.

Start-up of the disinfection system requires the participation of representatives of the contractor, equipment supplier, engineer, and utility operation and maintenance personnel. The utility personnel must take full advantage of this activity as operational modes are developed based on the advice of field representatives of the parties involved. These may be continued throughout the operational life of the facility.

Operating and maintenance personnel should be given sufficient time to review the various literature made available to them by vendors and the engineer. Information that is not readily understandable by utility personnel should be rejected immediately by the utility for resubmission and acceptance before the party responsible for the deficient material is released from his contractual obligation.

Additional efforts will be required to train replacement personnel and to refresh the skills and knowledge of current personnel. Although some training is provided at the facility on a "free" basis as part of promotional efforts by vendors or engineers, funds should be budgeted for the cost of attendance by appropriate utility personnel at local, state, or regional training sessions and technical seminars. Continual training is required on an in-house basis to maintain safety awareness as well as to maintain necessary operator skills.

A 'self-teaching' operator training program is being developed by the California State University, Sacramento, under contract to the Environmental Protection Agency. Dr. Kenneth D. Kerri is the Project Director. The complete program, with manual, is to be available in 1984 (42).

MANUALS, EQUIPMENT, AND SUPPLIES REQUIRED

The documents resulting from the construction of the disinfection facilities should be reviewed, inventoried, and filed. Two or more complete sets of the documents should be maintained by the utility as shown in Table XIV.

The documents for use by operation and maintenance personnel should be maintained in filing cabinets at a point or points readily accessible to them. Proper filing facilities are essential to enable the personnel to perform their tasks in an organized manner.

Tools, materials, and safety equipment, including those specific to the disinfection system, should be identified, inventoried and stored in the vicinity of the disinfection process. They should be designated and maintained as specific to the disinfection process so that they are readily available for regular and emergency use.

MONITORING

Monitoring of the disinfection process and its equipment covers four activities, which are as follows:

(1) evaluation of condition of process equipment;

(2) process quality control;

(3) distribution system quality control;

(4) regulatory agency monitoring and reporting requirements.

The process equipment and conditions must be monitored daily to assure the safe, continuous operation of the disinfection process. This activity may be as simple as

TABLE XIV

AVAILABILITY OF DISINFECTION SYSTEM DOCUMENTS

Description of Document	Readily Available to O&M Personnel	Utility Headquarters	Emergency File (Bank Vault)
As-built construction and specifications	One copy	Reproducible copy	Microfilm copy
Contractor's shop drawing submissions	One set	One set	Microfilm copy
Equipment	One set	One set	Microfilm copy
Vendors manuals	One set	One set	Microfilm copy
Engineer's O&M manual	One copy	One copy	Microfilm copy
Training manuals	One copy	One copy	---
Project construction file	One copy	One copy	Microfilm copy
Project administration file	---	One copy	Microfilm copy

recording the weight of chlorine in the gas cylinder currently in use to the more complex recording of temperature - pressure - flow measurements of an ozonation system. Operational condition monitoring serves the dual purpose of requiring that the operator physically inspect the installation on a regular basis, as well as providing "trend" information that may be helpful in future trouble-shooting activities.

Operational monitoring for all modes of the disinfection equipment is beyond the scope of this document. Details will be provided in the Operation and Maintenance manual to be provided by the design engineer and/or the system vendor. Additional information will be available in Reference 42.

Process control monitoring basically should focus on the quality of the water receiving the disinfectant, the effective dosage being applied, and the resulting concentration of disinfectant. Effective dosage of a disinfectant/oxidant may be measured by residual for the chlorine compounds, but other site-specific, surrogate measurements must be obtained for

UV or ozone disinfection. The dosage of disinfectant/oxidant must be sufficient to achieve the desired level of disinfection. However, overdosing unnecessarily increases water treatment costs, and, with the exception of ozone and ultraviolet radiation, actually will reduce water quality, in terms of increasing levels of dissolved solids and trihalomethanes.

Monitoring of process parameters must be performed daily, or even more frequently, if the water quality is highly variable. The raw data should be processed to establish relationships, such as chemical requirements compared to turbidity level. These relationships are valuable tools in process troubleshooting or as a manual control guide if the automatic control systems fail or are suspect.

The utility should carry out frequent inspections, sampling, and analyses throughout the system to assure the bacteriological safety of the water being provided to the system's consumers. Sampling points for chlorine residual measurement and bacteriological sampling should include the following:

- o treatment plant product;
- o flow from reservoir or storage tank;
- o key points in the distribution system;
- o consumer taps on dead end lines.

Conditions in the water distribution system are changing constantly, due to the many demands placed upon it. For example, an existing cross-connection may have no effect on the system until a heavy demand is placed on it, such as the prolonged use of a fire hydrant, which significantly reduces the system pressure. Reduced system pressure could allow a contaminant to enter the system through the cross-connection.

Regulatory agency reporting requirements were discussed in Section 2. Water samples must be tested periodically for coliforms by a state or EPA approved laboratory using either the membrane filter or multiple tube fermentation techniques. The frequency of bacteriological testing is the minimum required by law. The water utility likely will choose to have sampling and analytical tests performed more frequently by a local laboratory. This "in-house" data can be used to identify problems which may include:

- sampling and sample handling;
- distribution system operation; and
- treatment plant operation.

It should be clearly understood that the process quality control and distribution system quality control are the key factors in maintaining compliance with the regulatory agency monitoring and reporting requirements. A positive coliform test report to the regulatory agencies is the final indication that the waterworks has failed in its responsibility to provide the public with a safe, pathogen-free drinking water.

Appendix B includes sample forms for the recording of data from coliform sampling and analysis.

PREVENTIVE MAINTENANCE

Preventive maintenance (PM) is the key to reliable service and long equipment life. Setting up a good PM program requires a strong planning effort but, once established, it pays for itself throughout the life of the facility. Close attention to the scheduled PM activities will reduce annual operating costs and minimize failures.

A PM program is specific to the utility and the facility. However, the following guidelines can be provided for utility personnel setting up and working with a PM program for a disinfection system:

- o Gain a thorough knowledge of the facility through documents listed under MANUALS, EQUIPMENT, AND SUPPLIES REQUIRED;
- o Maintain a file for each process unit component;
- o Maintain a system which will provide a reminder of work to be performed weekly, monthly, seasonally, and annually;
- o Provide sufficient funds for rigorous application of the PM program.

Several proprietary PM programs exist which provide the user with the material to develop a proven PM system. One such system is the Envirotech Operating Services Simplified Automatic Maintenance (SAM) system which has been successfully applied in a number of wastewater treatment plants (43).

The utility may consider entering into maintenance and service contracts for certain process components such as ozone generators, electronic controls, and flow metering. The need for this type of assistance may decrease as utility personnel become more familiar with the equipment. Services quite frequently are provided by the vendors' local representative, but could be provided by any firm with the prerequisite skills and equipment.

The necessary personnel, tools, equipment and materials must be readily available to perform PM work to assure that it gets done.

EMERGENCY PROCEDURES

It is imperative that a written Emergency Procedures Manual be available to enable continuous operation of the disinfection process. Possible causes of interruption of disinfection must be identified and their solutions found and prepared for. Documentation of emergency procedures should clearly establish the hazards to utility personnel, utility facilities, the consumers, and the general public of various emergency situations. Restorative actions should be identified as well as those people responsible for taking that action. The emergency procedures should be practiced on a routine basis by utility personnel.

Every practicable means must be taken to continue to maintain the disinfection equipment in operation. These methods include:

- use of stand-by equipment maintained by the utility;
- use of stand-by equipment maintained by another utility;
- use of equipment available from a vendor.

The most practicable short-term solution for disinfection system emergency shutdowns would appear to be having available sodium hypochlorite solution fed by a manually controlled, positive displacement chemical feed pump operating on its own emergency backup power source. Sodium hypochlorite stored for emergency use should be tested periodically and replaced, if it is determined to have lost strength.

Possible emergency conditions include the following:

- failure of a key piece of equipment;
- interrupted chemical delivery;
- power failure;
- strikes;
- fire, flood, tornado, or other natural disasters.

For each problem, a check list of procedures to be followed should be available. Depending upon the type of emergency, one or more groups of interested parties will be contacted. These parties include the following:

- utility personnel;
- rescue, fire, police or emergency-management agencies;
- elected officials;
- regulatory agency personnel;
- consumers;
- chemicals suppliers;
- equipment vendors;
- local maintenance contractors;
- local construction contractors;
- equipment sales and rental firms;
- the media (radio, television, newspapers).

Updated lists of names, addresses, and telephone numbers should be maintained as part of the Emergency Procedures Manual.

Utility personnel must be briefed and trained in emergency procedures for a variety of potential emergency situations. Key situations such as a faulty chlorine cylinder should be identified and response procedures rehearsed to assure that personnel understand their roles and that the necessary response equipment is readily available and its use understood.

GOOD SANITARY PRACTICES

Flush the distribution system, particularly dead ends, on at least an annual basis to remove accumulated sediment. Clean and disinfect reservoirs and storage tanks annually, and repaint with commercial paints developed for clear water reservoirs.* Periodically clean and flush settling tanks, filters and other treatment equipment. Keep plant buildings clean and free from insect infestations and small animals (e.g., mice).

Maintain Close Liasion With Your Local Health Service And Medical Societies. Ask to be notified of any increase in patient load which might be attributable to waterborne infectious agents.

Conduct Periodic Sanitary Surveys Of The Watershed, Treatment Plant, And Distribution System

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* Information on commercial reservoir paints is available from the American Water Works Association, 6666 W. Quincy Avenue, Denver, Colorado, 80235, and from the Office of Drinking Water, U.S. EPA, 401 M Street, S.W., Washington, D.C. 20460.

All elements of the system, from source to distribution, and the surroundings, can be examined in a walking inspection. Faulty septic systems, leaking sewers, and high local concentrations of domestic animals or wildlife are particular sources of contamination.

Some of these elements are:

For Groundwater Sources

1) character of local geology;
2) slope of water table;
3) extent of drainage;
4) methods used to protect the supply against pollution from sewage or waste disposal;
5) various well construction features;
6) protection of supply wells at the top;
7) availability of a backup water supply;
8) treatment methods;
9) storage methods; and
10) distribution practices.

For Surface Water Sources

1) nature of surface geology;
2) population and sewered population per square mile;
3) character and efficiency of sewage treatment plants on watershed;
4) proximity of sources of fecal pollution to water supply intakes;
5) sources and proximity of industrial wastes;
6) character and quality of raw water;
7) measures used to protect watershed and reservoir against pollution;
8) adequacy of water treatment process to cope with specific contaminants in the specific raw waters;
9) adequacy and efficiency of pumping facilities; and
10) distribution practices.

Persons trained and skilled in either sanitary or public health engineering, (e.g., registered professional sanitary engineers) and having knowledge of both good engineering practices and the health aspects of waterborne diseases should conduct the sanitary surveys.

Protect Water Sources

Poorly enclosed well houses can allow small animals to pollute the source with droppings. A groundwater well can be contaminated by seepage around the well head if it is not properly grouted at the surface.

Check For Leaks In The Distribution System

Leaks in the distribution system not only lose water (hence revenues) and increase pumping costs, but also may allow pathogens a point of entry into the system.

Maintain Plant Operating Records

It is essential that good plant operating records be maintained. Such records also will help in operation -- for example, if chlorine usage increases it may be necessary to order the next shipment sooner. Operating records should contain checks of the various metering systems such as pressure recorders.

SAFETY PROCEDURES

The safety hazards associated with specific disinfection processes must be clearly identified by the utility personnel with the assistance of the engineer, equipment vendors, and chemical suppliers. Strong oxidizing agents can kill or injure. An initial step to provide protection against such disinfectants is to restrict access to the disinfection facilities. Access can be restricted by means of warning signs, fences, lock doors, and should be noted in utility procedural manuals.

Personnel authorized to operate and maintain the disinfection facility should be kept continually aware of the hazards of the disinfectants/oxidants in use. This familiarization should be achieved by formal training and retraining, signs, paint coding and practices in emergency procedures. Generalized guidance associated with the various disinfectants follows:

Gaseous Chlorine

1. Heat should not be applied to chlorine cylinders. If a higher gas rate is required, additional cylinders should be manifolded together.
2. The fusible plug of the cylinder should not be tampered with.
3. The cylinder hood should be kept in place except when the cylinder is in use.
4. The cylinder should not be lifted by its hood.
5. A cylinder should not be dropped or knocked over.
6. The chlorination system should be checked periodically for leaks. This is done using a rag dipped in strong ammonia solution (28% ammonia in water). Household ammonia is not strong enough for this activity.
7. Chlorine gas is heavier than air. Therefore, plant personnel should stay upwind of and uphill from a chlorine gas leak, unless protective breathing apparatus is being utilized.

Sodium and Calcium Hypochlorites

1. Store and handle using clean (both) and dry (calcium hypochlorite) implements, free of oils, grease, and other organic impurities.
2. Store in areas separate from all other chemicals with which they might react.
3. Immediately remove a leaking or defective container from the storage area.
4. Mix calcium hypochlorite solid only with water.
5. Protective equipment (face protection, gloves, aprons) must be worn when preparing and handling hypochlorite solutions.

Chlorine Dioxide

1. All safety precautions described for handling gaseous chlorine or sodium

hypochlorite (depending upon the method of generation of chlorine dioxide) should be practiced.

2. The chlorine dioxide generator room should be kept free of all organic materials.

3. Do not allow spills of sodium chlorite solution to dry. In the dry state, sodium chlorite is spontaneously combustible. Flush all spills, however small, with water promptly and thoroughly. Never allow organic materials (cloths, brooms, mops, etc.) to come in contact with concentrated solutions of sodium chlorite. They may ignite.

4. When strong mineral acid is used for the generation of chlorine dioxide, observe all safety precautions concerning spills and leaks of such materials.

5. Do not allow chlorine dioxide gas to escape from solution into the ambient plant atmosphere. Not only is chlorine dioxide gas toxic, but in certain concentrations in air, it can be explosive.

Chloramines

1. Observe the safety precautions described for chlorine gas or hypochlorite solutions.

2. Observe the same precautions for handling cylinders of liquid ammonia as for gaseous chlorine, although ammonia cylinders normally are not equipped with fusible plugs.

3. Note that ammonia gas is lighter than air and will rise.

Ozone

1. Avoid breathing ozone Although it has a characteristic odor, personnel exposed to ozone for prolonged periods of time at threshold levels may become insensitive to it, and thereby fail to detect ozone at higher levels which can be hazardous.

2. Equipment for monitoring ozone levels in the ambient atmosphere of work areas should be tested weekly and recalibrated when necessary.

3. In the event of an ozone leak, ventilate work areas completely.

4. Ozone generators and associated ozone/air gas handling systems should be purged for a minimum of 30 minutes with dried air (with power to the generator turned off) before opening the generator or breaking any piping systems. This will prevent ozone from escaping to the plant atmosphere.

5. When ozone diffuser contactors are to be emptied and entered by plant personnel, the contactors should be pressure ventilated for a minimum of 12 hours. Personnel entering purged ozone contactors should wear self-contained breathing apparatus.

Ultraviolet Radiation

1. UV radiation can damage eye tissues. Personnel should never look directly into a UV unit which is operating. To change UV bulbs, the electrical power to the unit should first be shut off.

Safety procedures which are established for plant personnel should be enforced rigorously. Enforcement is necessary not only for the protection of employees, but also to reduce potential liability of the utility.

NIPDWR COMPLIANCE

A complete program for delivery of safe and sanitary water must include a conscientious effort to comply with NIPDWR monitoring, analytical, and reporting requirements. These regulations, largely based on normal water utility practices, provide a framework for assuring sanitary water supplies at reasonable cost.

VII. CASE HISTORIES

Three case histories are presented in this section which illustrate the successful use of chlorine, chlorine dioxide and ozone technologies for disinfection of drinking water. These case histories are the following:

- White Haven, PA - Chlorination
- Hamilton, OH - Chlorine Dioxide
- Strasburg, PA - Ozone

White Haven and Strasburg are small systems. Hamilton, OH, with an average daily production of about 15 mgd (56,781 m^3), is not a small system. On the other hand, Hamilton represents the most successful use of chlorine dioxide by a U.S. water supply system for terminal disinfection, as of mid-1982.

Although chlorine dioxide now is used for some purpose by more than 100 water supply systems in the U.S., only a few apply it as the sole disinfectant (24). Vendors contacted were unable to identify a small water supply system (flow of less than 0.5 mgd -- 1,853 m^3/day) which uses chlorine dioxide as the terminal disinfectant. As has been clearly pointed out earlier in this document, there is no reason why ClO_2 cannot be applied successfully for disinfection in small water systems.

Fifteen U.S. water treatment facilities currently use ozone for some purpose (44), and thirteen of these plants have installed ozonation facilities since 1977. One of the most successful of these is an 18 mgd (68,137 m^3/day) plant at Monroe, MI, which uses ozone for oxidation of organics, taste and odor removal, and reduction in levels of TTHMs (45). Three systems which use ozone as the terminal disinfectant are Newport, DE, Strasburg, PA, and Casper, WY. The story of ozone treatment at Strasburg perhaps is the better known (46), and it has been selected for inclusion.

The authors were unable to identify a small water treatment system employing chloramine for disinfection. As a result, there is no case history available to illustrate this method of disinfection.

These case histories are presented to illustrate how these water supply systems undertook to evaluate and install the disinfection technologies selected. It should be recognized, however, that all three case histories involve the use of groundwater sources, and not surface waters. Good sanitary engineering practice dictates that surface water supplies use conventional treatment (coagulation, sedimentation and filtration) before the disinfection step.

WHITE HAVEN, PA

White Haven Borough, located in the Pocono mountains of northeastern Pennsylvania, has a population of about 1,000. Its water supply is located in the nearby mountains, approximately one mile from the Borough. Access is by a dirt road to the open reservoir, which is fed by springs and supplemented by a well. Daily flows are approximately 110,000 gpd (416.4 m^3/day), and vary between a low of 20 gpm (75.8 L/min) to a normal maximum of 200 gpm (758 L/min). Fire flows of 750 gpm (2,839 L/min) to 1,000 gpm (3,785 L/min) are possible. Chlorine contact is conducted in the 8-inch (20.3 cm) transmission line of approximately 5,000 feet (1,524 m) providing about an 18-min detention time at 750 gpm (2,839 L/min).

In 1979, the White Haven Borough Municipal Authority, the system owner, was faced with the problem of replacing an old hydraulically-driven hypochlorinator that was worn beyond repair. The remote location of the plant in the surrounding mountains made daily attention during wintertime time-consuming and costly. The hypochlorinator was not designed to allow flow-pacing, problems had been experienced with freezing pipes, and proper mixing of the hypochlorite solution was a continual problem. However, the old stone building which housed the hypochlorinator was subject to considerable leakage.

The Authority's objective was to install a disinfection system that could be flow-paced to maintain residual control and be capable of extended periods of wintertime operation with little or no attention. Additionally, the municipality did not want another hypochlorination system because of the considerable maintenance problems which had been experienced, the problem of maintaining a uniform solution, and the need for frequent attention.

Therefore, the goal became to select a system that would be responsive both to low flows and to the high flows required by fire demands. The system has no storage of disinfected water, so that disinfection also must be conducted during fire flows.

The White Haven Gas Chlorination System

In conjunction with their consulting engineers, White Haven officials decided upon a new gas chlorination system, which consists of the components listed below. A schematic diagram of the treatment process is presented in Figure 24.

- Wallace & Tiernan V-500 Gas Chlorinator
- Wallace & Tiernan 50-345 Dual Cylinder Scale
- Sta-Rite 3/4 HP JGD Booster Pump
- Mine Safety Appliance 457083 Gas Mask
- Ramapo Mark V Flow Meter with Transmitter
- Badger Model 2061 Recorder-Indicator-Totalizer
- Fiberglass Building

The treatment system achieves the objectives of the owner. Enough chlorine cylinders can be stored to last through winter periods of heavy snows. Two 150 lb (68.1 kg) chlorine cylinders with an automatic changeover valve are an integral part of the system. One cylinder lasts for about one month. In addition, larger quantities of chlorine can be ordered at each purchase, thus resulting in savings due to lower unit cost.

The new gas chlorination system was installed in early 1980. After startup and debugging, it has been operating in a satisfactory manner, with chlorine residuals

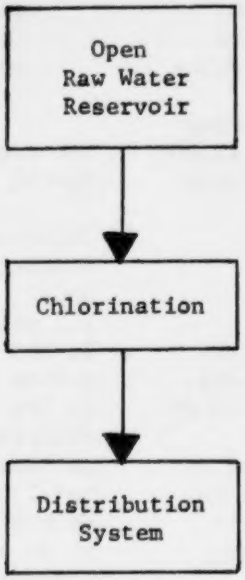
Open
Raw Water
Reservoir
Chlorination
Distribution
System

Figure 24. Schematic of Treatment Process at White Haven, PA

of 0.5 to 1.0 mg/L being maintained throughout the system.

Costs

The installed cost (January 1980) of the gas chlorination system, including pouring of a concrete pad for the building and installation by a local contractor, amounted to $15,749. Engineering fees of about 7%, or another $1,000, brought the total installed costs to $16,749.

HAMILTON, OH (29)

The 15 mgd (56,781 m^3/day) plant at Hamilton uses chlorine dioxide as the only disinfectant, although excess chlorine is present in solution because of the method of ClO_2 generation (excess chlorine gas is added to sodium chlorite solution). This lime softening plant obtains its raw water supply from deep wells (200 feet - 61 m). Chlorine was used as the disinfectant when the plant started operation in 1956, but because of customer complaints about chlorine tastes in the finished water, the plant switched to chlorine dioxide in 1972. Subsequently, the complaints have ceased. The groundwater contains trace amounts of iron and manganese, which are removed prior to ClO_2 treatment.

The Hamilton Water Treatment Process

A schematic flow diagram of the water treatment process used at the Hamilton plant is shown in Figure 25. The individual process steps include the following:

- aeration
- chemical addition (lime/alum)
- flash mix
- sedimentation
- recarbonation
- filtration
- chemical addition - sodium silicofluoride; ClO_2
- clearwell - distribution system

The Hamilton Chlorine Dioxide System

Chlorine dioxide is generated by mixing aqueous solutions of $NaClO_2$ (37%) and chlorine in a 1:1 weight ratio. This involves 20 lbs (9.08 kg) per day of sodium chlorite (dry basis) and 20 lbs (9.08 kg) per day of chlorine. Gaseous chlorine is delivered to the site in 150 lb (68.1 kg) cylinders. Sodium chlorite is shipped to the site by an area distributor in drums containing 200 lbs (90.8 kg) of 37% aqueous solution.

The chlorine dioxide generation system consists of a single plant-fabricated reactor vessel for ClO_2 production, one BIF peristaltic pump for sodium chlorite solution, and two Fisher & Porter chlorinators, one of which serves as a standby. The ClO_2 reactor vessel appears to be schedule 80 PVC (polyvinyl chloride) pipe material, 18 inches (45.7 cm) high and approximately 6 inches (15.2 cm) in diameter. The vessel is filled with 1-inch (2.54 cm) diameter PVC rings. The chamber is opaque and a sight glass is mounted "in-line" on the discharge piping. A white card is placed behind the sight glass to allow observation of the ClO_2 color.

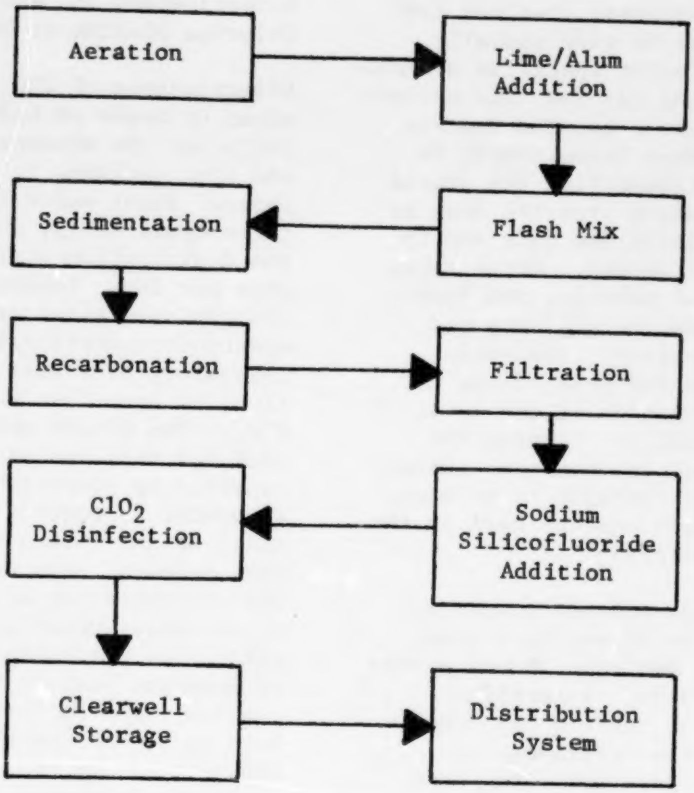
Aeration
Lime/Alum Addition
Flash Mix
Sedimentation
Recarbonation
Filtration
Sodium Silicofluoride Addition
ClO2 Disinfection
Clearwell Storage
Distribution System

Figure 25. Schematic of Treatment Process at Hamilton, OH

Two 150-pound chlorine cylinders are positioned next to the chlorinators. The weight of chlorine in the cylinders is measured by a scale. Switchover from one tank to the other is made manually. Fischer & Porter specifies schedule 80 PVC tubing for the line between the chlorinator and the reactor vessel. Heavy Tygon tubing is used for transporting the liquid $NaClO_2$ solution from the drum to a small plastic day tank and to the reactor vessel. After about one month of service, the Tygon tubing loses its rigidity and must be replaced. The semi-transparent day tank allows visual inspection of the level of $NaClO_2$ solution. Keeping the proper level in this tank thereby enables the operator to maintain an acceptable suction head on the peristaltic pump.

The chlorine dioxide generation equipment is housed in a room which does not have direct access to the outside. A corridor connects the room to the outside where chlorine cylinders are stored, but are protected from exposure to direct sunlight. There is an exhaust fan system in the ClO_2 room, but no chlorine leak detector. Both entrance doors to the chlorine dioxide room have glass panels for visual inspection of the room interior from outside of the room.

Production of ClO_2 is monitored visually (by the sight glass) by the characteristic golden-yellow color that appears inside the reactor vessel when the proper amounts of $NaClO_2$ and Cl_2 are mixed. Both the color of solution exiting the reactor and chemical feed rates are checked hourly, to ensure that the proper mix of chemicals for ClO_2 production is being maintained.

Effectiveness and Analysis of Chlorine Dioxide at Hamilton

Effectiveness of ClO_2 is determined by means of bacteriological tests and the absence of taste and odor problems in the finished water. Plant water is analyzed three times daily, while water in the distribution system is analyzed once per day. Levels of ClO_2 in the finished water are measured spectrophotometrically by plant laboratory personnel to concentrations of less than 0.2 mg/L as ClO_2. The H-acid method (10) is used for this analysis, which is reported by plant laboratory personnel to require a higher level of skill than other analytical test methods, such as OTA or DPD. The concentration of ClO_2 added to the plant water is 0.2 mg/L as ClO_2; this concentration generally is constant year-round. The ClO_2 residual leaving the plant is 0.15 mg/L, and the residual at the extremities of the distribution system is 0.10 mg/L.

Costs of Chlorine Dioxide Treatment at Hamilton

An EPA-sponsored team of investigators visited the Hamilton plant in late summer of 1977 (24). At that time, the cost of chlorine dioxide treatment at Hamilton was about 3.6¢ per capita per year. Chlorine and $NaClO_2$ together cost about $6,540 per year (1977 dollars). The fraction of total plant costs attributed to ClO_2 was reported to be negligible. Operating and maintenance costs for ClO_2 generation were estimated to be less than $50 per year in 1977 dollars.

The plant-fabricated ClO_2 reactor, piping, hardware, and installation were estimated by the plant supervisor to cost around $400, and the BIF peristaltic pump for $NaClO_2$ addition cost less than $200. To this $600 must be added the cost of the two chlorinators. Installation was performed by plant personnel.

Initial Consequences of Chlorine Dioxide Use at Hamilton

It was reported to the 1977 EPA survey team that the introduction of ClO_2 abated the problems caused by iron bacteria in the Hamilton distribution system. Consumers frequently had complained about the staining effects from tap water when chlorine was the disinfectant. However, when the plant switched from chlorine to chlorine dioxide as the disinfectant, brown slimes apparently were loosened from the mains and aggravated this situation even more. Plant personnel then flushed out the entire distribution system, and shortly thereafter, the complaints stopped. Plant personnel attributed the source of the problem to crenothrix and leptothrix bacteria (iron bacteria) that had been present in the extremeties of the distribution system before introduction of chlorine dioxide. This problem has not reappeared since ClO_2 was incorporated as the disinfectant.

STRASBURG, PENNSYLVANIA

The Borough of Strasburg is located in southeastern Pennsylvania in the heart of Pennsylvania Dutch country. With a population of about 2,000, Strasburg owns and operates its own water supply system, which serves the Borough and various farms between its reservoir and the town itself. It is the only small water system in Pennsylvania utilizing ozone as its primary disinfectant.

During EPA's National Organics Reconnaissance Survey of 80 municipal water supplies, conducted in 1974 and 1975 (47), less than 0.1 microgram of chloroform was found per liter of Strasburg's finished water supply. No traces of the other three trihalomethanes were found.

The water system, originally constructed in 1896, utilized 13 springs as its source until the mid-1970s, when additional springs and a well were added. Prior to 1973, the system had no disinfection capability until the Commonwealth of Pennsylvania by court order* ordered the Borough to install a disinfection process. Under significant pressure from customers not to install chlorination, the Borough opted to install an alternative (ozonation) disinfection system. This alternative disinfection system was approved by the Pennsylvania Department of Environmental Resources after the Borough agreed to install a chlorinator as backup.

The Borough had constructed a 500,000 gallon covered storage reservoir in the 1940s that is gravity-fed by the springs; two additional gravity-fed springs were added in 1977. Increases in customer demand and extended dry periods in 1980 resulted in water rationing and ultimately in the drilling of a well. This well is capable of producing 75 gal/min (284 L/min) and supplies 18,000 to 27,000 gal/day (60 to 102 m^3/day) to the system. The distribution system consists of 9,000 feet (2,743 m) of 12-inch (30.48 cm) and 12,000 feet (3,657 m) of 8-inch (20.32 cm) line. Present water usage of the system (1982) is approximately 140,000 gal/day (520 m^3/day), with a higher average of 180,000 gal/day (681 m^3/day) during summer months. No detailed tests have been made on the well to determine its ultimate capacity. Addition of the well to the water supply has relieved present water rationing, but the plant operator is uncertain if the system has adequate future capacity to service customers outside the Borough.

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* Under Title 25, Chapter 109 of the Pennsylvania Clean Stream Law, which requires disinfection of all water sources.

A schematic diagram of the Strasburg water treatment process is illustrated in Figure 26. The high quality groundwater requires only disinfection (by ozonation) and addition of soda ash for pH adjustment.

The Strasburg Ozonation System

The Borough's ozonation system consists of two tube-type, water-cooled ozone generators which were lease-purchased from the Welsbach Ozone Systems Corporation. Ozonation equipment is located in a 10 x 10 ft (3 x 3 m) cinder block building adjacent to the buried reservoir. The ozone generators are operated on two-month cycles; one is cleaned and checked by the operator on a rotating basis every two months. (The authors consider this frequent cleaning to be unusual. Most ozone systems are maintained on a six-month to one-year basis). All maintenance is performed by Borough personnel.

The system, originally installed in 1973 for $23,182 (cash price, not including lease-purchase agreement), initially fed 3.7 lbs/day (1.38 kg/day) of ozone into a water flow of approximately 110,000 gal/day (416 m^3/day) at an average dosage of 4 mg/L. This rather high ozone addition rate, dictated by Pennsylvania standards to provide a residual concentration of ozone equivalent to that of residual chlorine were it to have been used, resulted in customer complaints of milky water (caused by excessive amounts of air being added to the water along with the ozone). Subsequently, the State has allowed the Borough to lower the amount of ozone dosed to the water, and present practice is to dose at a rate of 0.67 mg/L of ozone -- less than one lb/day (464 g/day), an amount believed by the plant operator to be adequate for disinfection. The operator can measure the amount of ozone being produced only by testing for residual ozone in the treated water. This test is performed within the ozonation house using colorimetry. The rate of ozone generation is controlled manually by a rheostat.

For ozone generation, atmospheric air is pressurized by an air compressor, then dried by passage through a desiccant and fed to the generator. The Borough has spare parts for all units. Power outages have occurred during the past three years, the longest of which lasted two hours. The

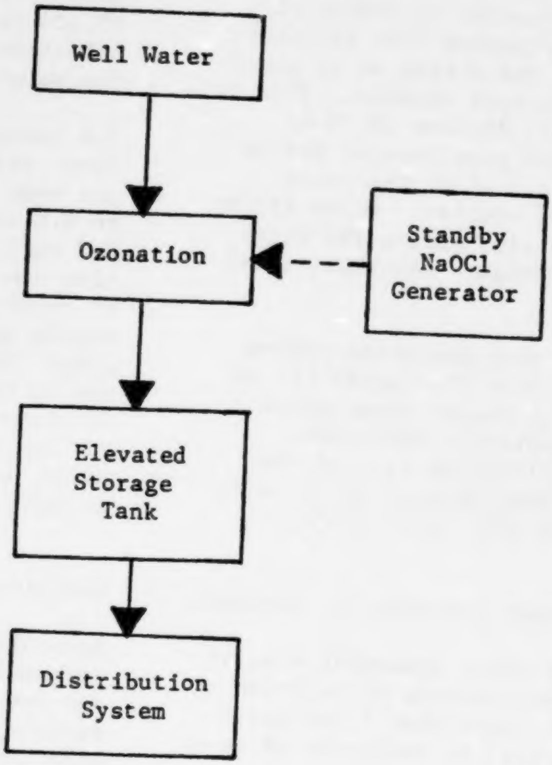
Well Water
Ozonation
Standby NaOCl Generator
Elevated Storage Tank
Distribution System

Figure 26. Schematic of Treatment Process at Strasburg, PA

standby chlorinator has been used only then and when the ozone generators were being repaired.

Ozone contacting equipment consists of a porous tube diffuser placed at the bottom of an underground concrete chamber. This is a vertical, 32-foot (9.75 m) underground pipe located within 20 feet (6.1 m) of the ozone generation shelter. Ozone (1% by weight in air) enters the diffusers through a stainless steel pipe.

The Strasburg ozonation system does not have the capability of destroying excess ozone present in the contactor off-gases. Atmospheric dispersion of the excess ozone appears to be sufficient for this rural plant.

Other Water Treatment At Strasburg

The only other treatment step at Strasburg consists of addition of soda ash (less than 5 lbs/day -- 2.27 kg/day) to raise the pH from 6.5 to 6.8-6.9.

Costs Of Ozonation At Strasburg

Power costs of operating the Strasburg ozonation system are $1,100 per year. This includes heating costs for the ozonation shelter, the only building structure possessed by the water system. Costs for soda ash are estimated at $600 per year. In the ozonation equipment, the glass dielectric tubes require unusually frequent replacement. Each of the two ozone generators has four tubes, and the Borough purchases an average of three replacement tubes per year. Replacement tubes and spare parts run about $600/yr at this plant.

Actual maintenance costs for the first nine months of 1982 (through September 30) were $830. The operator spends an average of six hours per week (at $10 per hour = $3,120 per year) to keep the ozonation system operable, and for water testing.

The operator performs pH and ozone residual tests three days per week to maintain a pH of 6.8 to 6.9 and an ozone residual of 0.7 mg/L in the system. Samples also are collected independently at other points in the water supply system by a local laboratory. Total water use in 1980 was 50 million gallons. The cost of treatment in 1980 was $108 per million gallons (per 3,785 m^3) of water, or about $0.11 per thousand gallons (3,785 L).

Additional Operator Comments

According to its operator, the Strasburg Water System has not had any problems with regulatory agencies regarding compliance with the requirements of the Safe Drinking Water Act. There is no ozone residual in the system at consumer taps; however there have been no complaints about the water, and no positive plate counts have been found in samples taken by the independent laboratory. The operator describes the well water quality as equal to that of spring water.

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APPENDIX A

DETAILED COST DATA

In the following discussion, cost data are presented for the following disinfection systems:

- solution-feed chlorination with chlorine gas;
- chlorination with sodium hypochlorite solution;
- chlorination with calcium hypochlorite solution;
- chlorine dioxide;
- chloramines;
- ozone;
- ultraviolet radiation.

Cost data presented are taken from Reference 39, where considered appropriate, and are supplemented by vendor quotes obtained for the various disinfection systems. Vendor quotes were obtained during the period 1980-1982.

Operating and maintenance costs presented do not include chemical costs. These will vary depending upon the volume of water treated and the dosage required. However, sample calculations are presented in this Appendix for determining quantities of each disinfectant. The reader then can calculate a total annual cost by employing the procedures presented in Section 5.

COSTS FOR CHLORINATION SYSTEMS

Solution-Feed Chlorination With Gaseous Chlorine

Equipment Costs

Table XV shows a detailed cost breakdown obtained during May 1980 from three prominent vendors of chlorination equipment. Data are presented in terms of a basic gas chlorination system, as well as costs for five increasingly complex systems. The basic system includes equipment to handle two 150-lb chlorine cylinders, two cylinder-mounted chlorine gas regulators, automatic changeover valve, and chlorine gas flow and rate valve ejector (with system backup). Alternate #1 adds two scales, a gas mask and a diffuser corporation cock (to allow connection under water line pressure). Alternate #2 adds a flow-pacing chlorine addition system. Alternate #3 adds a flow meter. Alternate #4 adds a booster pump and piping. Alternate #5 adds a chlorine leak detector.

TABLE XV

CAPITAL COSTS -- GAS CHLORINATION*

EQUIPMENT COSTS		
Basic System**	Avg.	$1,873
	High	$2,300
	Low	$1,320
Alternate 1 - add scales, mask diffuser, corp cock	avg.	770
Alternate 2 - add flow pacing - existing signal	avg.	1,694
Alternate 3 - add flow meter & signal, 8" or less	avg.	2,068
Alternate 4 - add booster pump & piping	avg.	792
Alternate 5 - add Cl_2 gas detector	avg.	1,382
INSTALLATION	avg.	1,167
	high	1,500
	low	1,000
SAFETY ENCLOSURE	avg.	3,500
	high	6,000
	low	2,000
CONTRACTOR'S OVERHEAD & PROFIT (20%)		1,869
ENGINEERING FEES (10%)		934
TOTAL CAPITAL COST:		
	Basic System	$9,343
	Most Sophisticated (with Alternate 5)	$16,049

* May 1980 quotes (three vendors)

** Basic system includes two 150-lb chlorine cylinders, two cylinder-mounted regulators, automatic changeover valve, chlorine gas flow and rate valve ejector (system with backup).

The size of this basic gas chlorination system is such as to be applicable to small water systems treating volumes of water at least up to 1 mgd. The larger systems will have to change chlorine cylinders more frequently than will the smaller systems. For example, a 1 mgd water treatment plant using an average chlorine dosage of 5 mg/L will use nearly 42 lbs of chlorine per day. Thus a 150-lb cylinder of chlorine will last between three and four days at this size plant.

The cost comparisons present a basic-to-most-sophisticated comparison between the various system configurations in which gaseous chlorination systems can be purchased. Costs in Table XV are comprised of equipment, installation, safety enclosure, contractor's overhead and profit, plus 10% engineering fee for the basic system estimates.

The basic (lowest cost) gaseous chlorination system costs about $9,350; with all options added, the most sophisticated gaseous chlorination system costs $16,050, in May 1980 dollars.

Operation and Maintenance Costs

Reference 39 states that in general, O&M costs for chlorination systems treating 2,500 gpd to 1 mgd are independent of flow. Process energy requirements are for the booster pump only and are about 1,630 kWh/yr. Building energy requirements for a 25 ft^2 building to house the system would be 2,560 kWh/yr. Maintenance material requirements would be only for miscellaneous repair of valving, electrical switches, and other equipment, and would total about $40/yr. Labor requirements are for periodic checking of equipment, with an average requirement of 0.5 hr/day, or 183 hr/yr.

O&M costs of $2,457/yr are summarized in Table XVI. Note that power costs were estimated at $0.07/kWh and labor at $10.00/hr. These rates were prevalent in 1982, and were used to update the corresponding energy and labor estimates originally made in Reference 39.

Chemical Costs

The costs of chemicals must be added to these O&M costs. In 150-lb cylinders, chlorine cost $0.47/lb in the Washington, DC area in January 1983. Taking a chlorine dosage rate of 5 mg/L for a sample calculation, gaseous chlorine chemical costs would be about $18/yr to treat 2,500 gpd and about $7,150/yr to treat 1 mgd. These costs were calculated as follows:

First, calculate the number of liters of water being treated per day. For a 2,500 gpd plant:

> 2,500 gal/day x 3.785 L/gal = 9,462.5 liters of water to be treated per day.

TABLE XVI

OPERATION AND MAINTENANCE SUMMARY FOR SOLUTION FEED GAS CHLORINATION

Item	Requirements*	Costs
Electrical Energy:		
Process	1,630 kw-hr/yr x $0.07 =	$ 114.10
Building	2,560 kw-hr/yr x $0.07 =	179.20
TOTAL	4,190 kw-hr/yr x $0.07 =	293.30
Maintenance Material		$ 40/yr
Labor	183 hr/yr x $10/hr =	$1,830
TOTAL ANNUAL O&M COST		$2,457

* estimates of energy, maintenance and labor made in Reference 39

Next, determine the number of milligrams of chlorine required per day. If the average chlorine dosage is 5 mg/L:

9,462.5 L x 5 mg/L = 47,312.5 mg/day

Then convert the number of mg required to pounds required per day:

47,312.5 mg x 1 g/1,000 mg = 47.31 g x 1 lb/454 g = 0.104 lb of chlorine required per day for a 2,500 gpd facility.

Finally, multiply the number of pounds of chlorine required per day by 365 (days per year), and that figure by the current cost of chlorine:

0.104 lbs chlorine required/day x 365 = 37.96 lbs x $0.47/lb = $17.84/yr.

A 1 mgd facility operating at design capacity treats 400 times as much water as does a 2,500 gpd plant (1,000,000/2,500 = 400). Therefore, a 1 mgd facility using a 5 mg/L chlorine dosage will require 400 times the amount of chlorine annually:

37.96 lbs Cl_2 x 400 = 15,840 lbs/yr x $0.47 = $7,445/yr.

To calculate costs for gaseous chlorine at lower or higher dosages, the following formula can be used:

$$\frac{\text{dosage (mg/L)} \times \text{no. of L dosed/day} \times Cl_2 \text{ cost/lb}}{1000 \text{ (mg/g)} \times 454 \text{ (g/lb)}} = Cl_2 \text{ cost/day}$$

Sodium Hypochlorite Solution Feed

Equipment Costs

Table XVII displays estimates obtained in May 1980 from two vendors of sodium hypochlorite chlorination equipment. Data are presented for the basic liquid hypochlorination system [which includes two metering pumps (one to be standby), solution tank, diffuser and appropriate quantities of tubing]. However, two types of basic systems are costed, one activated electrically and the other activated hydraulically. The basic systems can be supplemented, and costs for four increasingly sophisticated alternatives also are presented in this table. Alternate #1 adds a diffuser corporation cock and anti-siphon backflow preventer, Alternate #2 adds a safety housing enclosure, Alternate #3 adds a flow-pacing system, and Alternate #4 adds a flow meter and signal.

The total capital costs for the basic and most sophisticated systems are:

TABLE XVII

CAPITAL COSTS -- LIQUID CHLORINATORS*

EQUIPMENT COST (Basic System**)		Electric Activated	Hydraulic Activated
	avg.	$ 1,800	$ 2,266
	high	2,300	2,782
	low	1,300	1,750
INSTALLATION		500	1,000
SITE WORK		250	250
CONTRACTOR'S OVERHEAD & PROFIT (20%)		729	1,004
ENGINEERING FEES (10%)		364	503
Alternate 1: add diffuser corporation cork & anti-siphon backflow preventer		165	231
Alternate 2: add safety enclosure (housing)		6,930	6,930
Alternate 3: add flow pacing existing signal		-	1,485
Alternate 4: add flow meter & signal, 8" or less		-	1,452
TOTAL CAPITAL COST:			
Basic System (Equipment + Installation + Site Work + Overhead & Profit + Engineering Fees)		$ 3,643	$ 5,023
Most Sophisticated (with Alternate 2)		10,738	-
(with Alternate 4)		-	15,121

* May 1980 quotes (two vendors)

** Basic system includes two metering pumps (one standby), tubing, solution tank and diffuser.

	basic system	most sophisticated system
electrically activated	$ 3,643	$10,738
hydraulically activated	$ 5,023	$15,121

Operating and Maintenance Costs

As is the case with solution-feed gas chlorination, Reference 39 states that O&M requirements are independent of flow for plants handling 2,500 gpd to 1 mgd. Process energy requirements are for the diaphragm metering pump and amount to 570 kWh/yr. Building energy requirements for a 25 ft^2 building would be 2,560 kWh/yr. Maintenance material would be required only for minor component repair; these costs are estimated at $20/yr.

Labor is required for periodic mixing of the sodium hypochlorite solution, as well as for checking of the equipment. Based on a requirement of 1 hr/day, the annual labor requirement would be 365 hr/yr.

Annual O&M costs of $4,108 are summarized in Table XVIII. Note again that power costs are based on $0.07/kWh and labor costs of $10.00/hr.

Chemical Costs

Sodium hypochlorite is sold as a 1.5 to 15% (by weight) solution. In January 1983, the cost of a 15% solution in 1,500 gal tanks in the Washington, DC area was $0.93/gal.

How many gallons of 15% sodium hypochlorite (NaOCl) solution are required to dose 2,500 gpd of water with 5 mg/L of chlorine?

In the preceeding example, it was determined that 2,500 gpd of water using an assumed 5 mg/L dosage of chlorine requires 0.104 lb of chlorine per day. One gallon of hypochlorite solution weighs approximately 8.34 lbs and contains 15% by weight of NaOCl. Therefore, 1 gal of 15% NaOCl solution contains 8.34 x 0.15 = 1.251 lb of NaOCl. However, one lb of NaOCl contains 47.65% available chlorine. Therefore, one gal of 15% NaOCl solution contains 1.251 lb of NaOCl x 0.4765 = 0.596 lb of available chlorine.

Since only 0.104 lb of available chlorine is required per day, then 0.104/0.596 = 0.175 gal/day of 15% NaOCl solution is required to provide a 5 mg/L dose of chlorine.

Over 365 days (one year), the amount of 15% NaOCl solution required is 0.175 x 365 = 63.7 gal. At $0.93/gal, the 2,500 gpd utility will spend about $59.24/yr (at an average dosage of 5 mg/L of chlorine). A 1 mgd facility will require 400 times more hypochlorite, and will spend $23,696/yr for the 15% solution.

TABLE XVIII

OPERATION AND MAINTENANCE SUMMARY FOR SODIUM HYPOCHLORITE SOLUTION FEED

Item	Requirements*			Cost
Electrical Energy:				
Process	570 kw-hr/yr	x	$0.07 =	$ 39.90
Building	2,560 kw-hr/yr	x	0.07 =	179.20
TOTAL	3,130 kw-hr/yr	x	0.07 =	219.10
Maintenance Material				$ 20/yr
Labor	365 hr/yr	x	$10/hr =	3,650
TOTAL ANNUAL O&M COST				$4,108

* amounts estimated in Reference 39

Calcium Hypochlorite Solution Feed

Equipment costs and operating and maintenance costs for this method of disinfection should be very close to those for sodium hypochlorite feed systems. Solutions of calcium hypochlorite are prepared in a day tank (a tank which holds enough solution to last for one day), then injected into the water stream using a diaphragm metering pump.

Chemical Costs

Solid calcium hypochlorite, $Ca(OCl)_2$, contains 65% available chlorine. Therefore, one lb contains 0.65 lb of available chlorine. Since a 2,500 gpd water treatment plant requires 0.104 lb of chlorine per day (for an average dosage of 5 mg/L), 0.104/0.65 = 0.16 lb of $Ca(OCl)_2$ per day is required with which to prepare a solution for metering into the water to be treated.

During January 1983, calcium hypochlorite was selling for $1.40/lb in 100 lb bags in the Washington, DC area. Over a one year period, the 2,500 gpd facility will require 0.16 lb x 365 days = 58.4 lbs of $Ca(OCl)_2$, x $1.40/lb = $81.76/yr. The 1 mgd facility, which uses 400 times the amount of chlorine, therefore will spend $32,704/yr for $Ca(OCl)_2$.

Costs For Chloramination

Generation of chloramine requires the same equipment for chlorination (gaseous or aqueous hypochlorination) plus equipment for the addition of ammonia (gaseous or aqueous). Costs for chlorination equipment and for its operation and maintenance have been discussed above; in this section, costs for addition of ammonia are presented.

Ammonia is available in either of three forms:

- anhydrous ammonia (100% available ammonia);
- 28% solution in water, called aqua ammonia (28% available NH_3);
- solid ammonium sulfate (25.76% available NH_3).

For small water supply systems, anhydrous ammonia is purchased as a pressurized liquid in 150-lb cylinders. It is fed as a gas to the point of application. Aqua ammonia is purchased in 55-gallon drums, and food grade ammonium sulfate is purchased as a solid in 100-lb bags.

During January 1983, costs for liquid ammonia were $0.40/lb (in 150-lb cylinders), $0.70/lb of contained ammonia in 28% solution (purchased in 55-gal drums), and $0.51/lb for solid ammonium sulfate (purchased in 100-lb bags), in the Washington, DC area.

Cost calculations given below are based upon the following reaction of chlorine gas and ammonia to produce monochloramine:

$$NH_3 + Cl_2 \longrightarrow ClNH_2 + HCl$$

In addition, the calculations assume a 5 mg/L dosage of disinfectant, in this case 5 mg/L of monochloramine, which is obtained either by adding the proper amount of chlorine to water, then adding the requisite amount of ammonia, or vice-versa. It is also assumed that all chlorine added will be free available chlorine, and will be utilized during reaction with ammonia to produce monochloramine. This does not strictly reflect actual water supply situations, because some chlorine demand is usually present for producing trihalomethanes, if chlorine is added prior to ammonia. Therefore, these calculations reflect the minimum amounts of chlorine which will be required to produce a 5 mg/L dosage of monochloramine.

Finally, cost calculations will be given based upon chlorine added as the gas. By using previously described calculations involving solutions of sodium hypochlorite or of calcium hypochlorite, the amounts of these chlorinating agents required to produce monochloramine can be calculated readily.

Costs For Monochloramine From Anhydrous Ammonia + Chlorine Gas

A 2,500 gpd water treatment plant will require 0.104 lb/day (47.31 g/day) of monochloramine at a dosage of 5 mg/L. According to the chemical stoichiometry of the equation given above for the generation of monochloramine from ammonia and chlorine, each gram-molecular weight (weight of one mole of compound expressed in grams) of monochloramine produced will require 1 gram-molecular weight each of ammonia and chlorine. Thus:

$$17\text{ g } NH_3 + 71\text{ g } Cl_2 \longrightarrow 51.5\text{ g } ClNH_2 + 36.5\text{ g } HCl$$

Since 47.31 g/day of monochloramine are required each day, the corresponding amounts of ammonia and chlorine required are:

Ammonia: (47.31/51.5) x 17 = 15.62 g/day

Chlorine: (47.31/51.5) x 71 = 65.22 g/day

Dividing the grams of each reactant by 454 (the number of grams per pound), gives a daily requirement of 0.034 lb of ammonia and 0.143 lb of chlorine.

Multiplying each of these figures by 365 days yields the annual number of pounds of ammonia and chlorine required. Finally, annual costs for each are calculated by multiplying the annual requirements by the current costs:

Ammonia: 0.034 lb/day x 365 = 12.41 lb/yr x $0.40/lb = $4.96/yr

Chlorine: 0.143 lb/day x 365 = 52.20 lb/yr x $0.47/lb = $24.53/yr.

The sum of these two numbers ($4.96 + $24.53) = $29.49, total annual chemical costs for the 2,500 gpd facility.

A 1 mgd facility will require 400 times the amounts of chemicals at the same 5 mg/L dosage, therefore:

$29.49 x 400 = $11,796/yr, annual chemical costs.

Costs For Monochloramine From Aqua Ammonia + Chlorine Gas

From the preceeding calculations, the 2,500 gpd facility will require 12.41 lbs/yr of anhydrous (gaseous) ammonia. If the source of ammonia is 28% aqueous ammonia, the calculation of the costs is as follows:

1 gal of 28% ammonia weighs 8.34 lbs and contains 8.34 x 0.28 = 2.34 lbs of ammonia.

12.41 lbs/yr ammonia requires 12.41/2.34 = 5.3 gal/yr of aqua ammonia.

At $0.70/lb of ammonia contained in aqua ammonia, the annual cost of aqua ammonia is:

12.41 lbs x $0.70/lb = $8.69/yr.

The annual cost of gaseous chlorine is $24.53/yr, therefore the total annual chemical costs are:

$8.69 + $24.53 = $33.22/yr.

The 1 mgd water treatment plant will require 400 times the amounts of chemicals:

$33.22/yr at the 2,500 gpd plant x 400 = $13,288/yr at the 1 mgd plant.

Costs For Monochloramine From Ammonium Sulfate + Chlorine Gas

One pound of ammonium sulfate contains 0.2576 lb (28.76%) of available ammonia. The 2,500 gpd plant using solid ammonium sulfate will require 12.41 lbs/yr of anhydrous ammonia annually. To obtain this amount of available ammonia requires 12.41/0.2576 = 48.18 lbs/yr of ammonium sulfate. At $0.51/lb current cost, the 2,500 gpd plant will require:

48.18 lbs/yr x $0.51/lb = $24.57/yr + $24.53 for chlorine = $49.10/yr.

The 1 mgd facility will require 400 times as much chemicals, or:

$49.10 x 400 = $19,640/yr.

TABLE XIX

COMPARATIVE ANNUAL O&M AND CHEMICAL COSTS FOR CHLORINE AND MONOCHLORAMINE (ASSUMED 5 mg/L DOSAGE)

Disinfectant Source	2,500 gpd plant costs			1 mgd plant costs		
	O&M	Chemical	Total	O&M	Chemical	Total
Chlorine:						
gaseous chlorine	$2,457	$17.84	$2,475	$2,457	$ 7,445	$ 9,902
NaOCl solution	4,108	59.24	4,167	4,108	23,696	27,804
$Ca(OCl)_2$ solution	4,108	81.76	4,190	4,108	32,704	36,812
Chloramine (from gaseous chlorine):						
anhydrous NH_3	2,457	29.49	2,486	2,457	11,796	14,253
aqua ammonia	2,457	33.22	2,490	2,457	13,288	15,745
ammonium sulfate	2,457	49.10	2,505	2,457	19,640	22,097

Summary of Chlorination Costs

Table XIX summarizes the annual operation and maintenance and chemical costs for the three types of chlorination (gaseous, hypochlorite solution, and calcium hypochlorite) plus chloramination (prepared from anhydrous ammonia, aqua ammonia and ammonium sulfate) using gaseous chlorine. Annual chemical costs are calculated for 2,500 gpd and 1 mgd plants based on a 5 mg/L dosage of chlorine or of monochloramine. This dosage was selected solely for convenience in calculating exemplary costs for controlling microorganisms with chlorine, hypochlorite or chloramines. It is not a recommended dosage.

O&M costs are the same at each size plant, since they are independent of flow. O&M costs for solution feed of either sodium hypochlorite or calcium hypochlorite are identical because the same equipment is used in both cases. O&M costs shown for chloramine are identical because gaseous chlorination has been assumed for these calculations. If monochloramine is made using sodium hypochlorite or calcium hypochlorite solutions, O&M costs will be higher ($4,108 versus $2,457) because O&M costs for feeding solutions are higher.

It is apparent from the data of Table XIX that the annual chemicals costs at the 2,500 gpd plants are only 1 to 2% of the annual O&M costs. However, at the 1 mgd plants, annual chemical costs are 3 to 8 times the annual O&M costs. Costs at intermediate sized plants will be increasingly dependent upon chemical costs as plant sizes increase.

It should also be noted that the cost of chlorination using gaseous chlorine is 36% of the cost of using sodium hypochlorite solution, and 27% of the cost of using calcium hypochlorite.

COSTS FOR CHLORINE DIOXIDE

Reference 39 summarizes costs for generation of chlorine dioxide from equal parts of 2.4% sodium chlorite solution, 25% sulfuric acid solution and 1% sodium hypochlorite solution. Suppliers contacted in 1982 have designed their generation systems for small water supply systems to use 33% hydrochloric acid rather than 25% sulfuric acid.

The cost estimates of Reference 39 assume the use of a dual head diaphragm pump for simultaneous addition of the hypochlorite and acid solutions, and a second single head pump for the addition of sodium chlorite solution. Detention time in the chlorine dioxide reactor is estimated at 12 seconds, and the costs of generating equipment are assumed constant up to 50 lbs/day of chlorine dioxide. The recommended maximum dosage rate for chlorine dioxide is 1 mg/L. At this maximum dosage rate, a 1 mgd water treatment plant would use about 8 lbs/day and a 2,500 gpd facility would use about 0.2 lb/day of chlorine dioxide.

Equipment Costs

Quotes were obtained from three suppliers of chlorine dioxide generation equipment sized so as to prepare ClO_2 at the rate of 8 lbs/day. This low production volume would be required by a 1 mgd plant, dosing chlorine dioxide at a maximum rate of 1 mg/L, as is currently recommended by EPA (11). These quotes (obtained in June 1982) are shown in Table XX. The recirculating loop system made by a French manufacturer is the highest in equipment price; their lowest cost unit is priced at $34,000. This unit operates with a special recirculating pump designed to handle hypochlorous acid solution at pH below 4, plus a sodium chlorite solution pump and all necessary instrumentation to allow automatic operation, with shutdown provisions in the event that water flow ceases.

Next lowest in price is the system from Supplier B, which generates chlorine dioxide from 33% hydrochloric acid, 12% sodium hypochlorite solution and 25% sodium chlorite solution. This unit costs $25,000 (installed), and includes three solution pumps, water flow rate detector and switches to shut down the unit if the water flow stops. This unit is wall-mounted and requires 3.5 ft x 4 ft of wall space, plus space for drums of the three chemical solutions used to feed the generator. For volumes of ClO_2 sufficient to treat flows in communities of 5,000 and 2,500 population, this unit is said to be capable of continuous operation, with no loss in efficiency of conversion of chlorite ion to chlorine dioxide. However, to supply the needs of systems serving as few as 25 people, the unit would have to be operated intermittently, with ClO_2 solution being stored in a holding tank for later metering into the water.

Finally, Supplier C provides two types of generators for small water supply systems: one uses acid/sodium chlorite; the other uses chlorine gas and sodium chlorite. These units cost $3,600, if wall-mounted, and $4,320 for a floor mounted cabinet. The single size unit currently offered by this company will produce up to 140 lbs/day. In order to produce 8 lbs/day or less on a continuous flow basis, this unit would have to be operated at such low solution flow rates as to provide inefficient mixing, and, therefore, poor conversions of the reactants to chlorine dioxide. Therefore small water supply systems considering the use of this unit also will have to install a holding tank for the product and operate the generator intermittently at design rates of solution flows.

The chlorine gas/sodium chlorite ClO_2 generator of Supplier C requires a gas chlorinator in order to feed chlorine gas. Therefore, in new plants considering use of this generator, the cost of a chlorinator must be added to the cost of the ClO_2 generator. In existing plants currently using gas chlorination, the chlorinator already is in place and would not represent an added equipment cost.

TABLE XX

1982 VENDOR QUOTES -- CHLORINE DIOXIDE GENERATORS

Vendor	ClO2 production capacity (lbs/day)	space required*	Reactants	Unit Cost
recirculating loop Supplier A (French)	1-10	2'x3'x6' high	Cl_2 gas + $NaClO_2$ solution	$34,000 (1 rate, adjust manually)
				$38,000 (2 rates, adjust automatically)
				$41,700 (3 rates, adjust automatically)
				prices delivered in New York
Supplier B	4	3.5'x4'x 1.5' deep (wall-mounted)	HCl, NaOCl, $NaClO_2$ solutions	$25,000 (installed)
Supplier C	14-140	4'x3'x 1.5' deep	Cl_2 gas & $NaClO_2$ solution	$ 4,320** (floor mounted)
		37.5"x 27" 6.5" deep	same	$3,600** (wall mount)
Supplier C	14-140	4'x3'x 1.5' deep	HCl + $NaClO_2$ solution	$4,320 (floor mounted)
		37.5"x27" x 6.5" deep	same	$3,600 (wall mounted)

* all units require additional space for solution tanks.

** this unit requires a chlorinator for operation, which is not included in price estimates

TABLE XXI

OPERATION AND MAINTENANCE SUMMARY FOR CHLORINE DIOXIDE GENERATING AND FEED SYSTEMS

Item	Requirements*	Cost
Electrical Energy:		
Process	1,240 kw-hr/yr x $0.07 =	$ 86.8
Building	4,100 kw-hr/yr x $0.07 =	$ 287.0
TOTAL	5,340 kw-hr/yr x $0.07 =	$ 373.8
Maintenance Material		$ 100/yr
Labor	365 hr/yr x $10.00 =	$3,650
TOTAL ANNUAL O&M COST		$4,124

* based on estimates made in Reference 39

Because equipment quotes for generating chlorine dioxide vary so widely, small water system personnel are advised not to try to apply indices to update older cost estimates. Technology for generating and applying chlorine dioxide is changing (as opposed to technologies for addition of gaseous or aqueous chlorine) and new suppliers enter the market from time to time. It is more advantageous to seek quotations from the various suppliers as to the various methods of generating ClO_2. Select the method most appropriate to the specific plant, then determine what piping and wiring will be needed to install the equipment selected.

Operating and Maintenance Costs

Reference 39 states that, in general, O&M costs for generating ClO_2 are independent of the quantities generated. Process energy requirements, which are for metering pumps and mixer for preparing chlorite solution from solid sodium chlorite, are estimated at 1,240 kWh/yr. Energy requirements for 40 ft^2 of building space to house the equipment would be 4,100 kWh/yr, resulting in total energy requirements of 5,340 kWh/yr. Maintenance material requirements would be for minor equipment repair only, amounting to about $100/yr. Labor is required for preparation of solutions and periodic maintenance of the equipment. Annual labor requirements are estimated to be 1 hr/day or 365 hr/yr.

Annual O&M costs of $4,124/yr (based on $0.07/kWh power cost and $10.00/hr labor cost) are summarized in Table XXI.

Chemical Costs

At an annual ClO_2 production rate of only 8 lbs/day (maximum at a 1 mgd plant), chemical costs are not as significant as pumping costs. Nevertheless, gaseous chlorine costs $0.47/lb, sodium chlorite costs $1.55 to $1.65/lb (as solid or in solution), hydrochloric acid costs about $0.10/lb, and sodium hypochlorite costs $0.93/gal for 15% solution. A production rate of 8 lbs/day equates to 2,920 lbs/yr of chlorine dioxide. If the chemicals cost of ClO_2 is arbitrarily assumed to be $1/lb, a 1 mgd water treatment plant can expect to pay $2,920 in addition to the annual O&M costs. Chemical costs at a 2,500 gpd plant would be $2,920/400 = $7.30/yr for producing chlorine dioxide at $1.00/lb.

COSTS FOR OZONATION SYSTEMS

Equipment Costs

These will include estimates for ozone generation equipment and ozone contacting systems, both of which are supplied by the ozone systems manufacturer. Water supply systems treating 0.5 mgd and less will require a daily ozone generation capacity of from three to 21 pounds, and will be able to dose ozone at average levels of up to 3-5 mg/L. At these production levels, ozone will be generated from dried air, not oxygen, in order to avoid the costs of oxygen recovery and recycle equipment.

Ozonation equipment to be purchased includes the following:

- air preparation equipment (drying and chilling)
- ozone generator
- ozone contactor
- ozone destruction unit
- instrumentation and controls

For the small production quantities of ozone required by small water treatment plants (three to 21 pounds per day) items 1, 2, 4, and 5 can be assembled into a single, skid-mounted unit. If the contactor selected is a turbine type, even the ozone contactor is small enough to be included in the skid-mounted assembly unit.

Diffuser contactors for small ozonation systems generally are constructed of polyvinyl chloride (PVC) pipe standing on end, or of fiberglass reinforced plastic (FRP) tanks. A contact chamber containing diffusers should be approximately 18-ft high, providing a water depth of 16-ft and a detention time of 10 to 15 minutes. These conditions will insure the maximum transfer of ozone from gas phase to aqueous solution when employing diffuser contacting systems.

Equipment cost estimates were obtained from three of the major U.S. ozonation systems suppliers in 1982. These are presented in Tables XXII, XXIII, and XXIV for various daily ozone generation rates. Ozone Supplier A (Table XXII) provided estimates for ozone dosages of 3 and 5 mg/L at water flow rates of 500,000 gpd, 350,000 gpd and 180,000 gpd. This cost breakdown shows that equipment costs for air pretreatment and ozone generation capacity available from this supplier depend upon the dosage required at a particular water flow rate. In addition, the size (and cost) of the ozone destruction units required also varies, as does the power requirement to operate the total ozonation system.

Ozone Supplier A can provide four monitors with his system (all are optional, but all are recommended for optimal performance and minimal downtime). These will monitor:

- the dew point in the air preparation unit;
- ozone output of the generator;
- ozone in the ambient plant air (in case of leaks);
- dissolved ozone residual in the water.

The cost of these four monitors is constant at $15,000, regardless of system size in the range shown in Table XXII (5 to 21 pounds per day).

Table XXIII shows similar cost data for equipment of Ozone Supplier B. In this case, equipment costs are presented for water flows of 100,000, 200,000, 300,000, 400,000 and 500,000 gpd. Average ozone dosages are taken to be 3 mg/L, and the daily ozone output required varies from 3 lbs/day for treating 100,000 gpd to 15 lbs/day for treating 500,000 gpd.

TABLE XXII

COSTS OF OZONATION EQUIPMENT FOR SMALL WATER SUPPLY SYSTEMS (Company A - May 1982)

Size of water supply	500,000 gpd		350,000 gpd		180,000 gpd	
Maximum dosage of ozone (mg/L) at peak flow	5	3	5	3	5	3
Daily ozone requirement (lbs)	21	14	14	7	7	5
Contact chamber diameter (14 ft high, 4 compartments, 4 diffusers, Derakane fiberglass reinforced plastic)	6 ft	6 ft	5 ft	5 ft	4 ft	4 ft
EQUIPMENT COSTS						
Air preparation + ozone generation unit	$31,500	$25,000	$25,000	$22,000	$22,000	$19,500
Contact chamber with diffusers	$11,500	11,500	10,200	10,200	z 9,900	z 9,900
Monitoring Instrumentation 1) Ozone in generator product 2) Ozone in ambient plant air 3) Ozone dissolved in water 4) Dew point monitor in air preparation unit	$15,000	15,000	15,000	15,000	15,000	15,000
Ozone Destruction Unit	$6,700 (10 cfm)	5,000 (7 cfm)	5,000 (7 cfm)	4,200 (3 cfm)	z 4,200 (3 cfm)	4,200 (3 cfm)
TOTAL EQUIPMENT COSTS	$64,700	$56,500	$55,200	$51,400	$51,100	$48,600
Power requirement kWh	13.3	10.1	10.1	5.0	5.0	3.65

TABLE XXIII

COSTS OF OZONATION EQUIPMENT FOR SMALL SUPPLY SYSTEMS (Company B - May 1982)

Flow Rate	0.1 mgd		0.2 mgd		0.3 mgd		0.4 mgd		0.5 mgd	
Maximum ozone dosage, (mg/L), at peak flow	3		3		3		3		3	
Daily ozone requirement (lbs/day)	3		6		7		12		14	
Equipment Costs	LP**	HP***	LP	HP	LP	HP	LP	HP	LP	HP
Air preparation + ozone generator*	-	$17,500	$33,200	$30,200	$38,500	$35,500	$43,000	$40,000	$49,800	$46,800
Power requirements (kWh/lb of 03 generated)	10.5	20	10.5	13.5	10.5	13.5	10.5	13.5	10.5	13.5
Ozone contactor with diffusers	$8,500		$12,000		$16,000		$21,000		$29,000	
Ozone Monitors										
- 03 generation****	$4,000 or 2,000		$4,000 or 2,000		$4,000 or 2,000		$4,000 or 2,000		$4,000 or 2,000	
- 03 room or contact chamber exhaust	2,200		2,200		2,200		2,200		2,200	
- dew point	3,500		3,500		3,500		3,500		3,500	
TOTAL EQUIPMENT COSTS	-	$33,700- 35,700	$54,900- 52,900	$51,900- 49,900	$64,200- 62,200	$61,200- 59,200	$73,700- 71,700	$70,700- 68,700	$88,500- 86,500	$85,500- 83,500

* includes air preparation, ozone generation, ozone destruction and system controls.

** air preparation unit includes air filters or separators, compressor delivering air at 8-12 psig to a refrigerative cooler and a dual tower desiccant dryer.

*** same as LP air preparation system, except compressor delivers air at 80-120 psig. HP system takes less space requires less maintenance, but requires more energy.

**** $4,000 instrument is an automatic, continuous reading in-line monitor. $2,000 instrument is not automatic and utilizes wet chemistry.

TABLE XXIV

COSTS OF OZONATION EQUIPMENT FOR SMALL SUPPLY SYSTEMS (Company C - February 1983)

Flow Rate	0.1 mgd	0.2 mgd	0.3 mgd	0.4 mgd	0.5 mgd
Maximum ozone dosage (mg/L) at peak flow	3	3	3	3	3
Daily ozone requirement (lbs/day)	2.5	5	7.5	10	12.5
Equipment Costs*	\$38,000	\$44,000	\$49,700	\$61,800	\$68,700
Ozone Monitors**	\$15,875	\$15,975	\$15,875	\$15,875	\$15,875
Power Requirement (kWh/lb O_3 generated)	16.2	14.6	13.6	12.3	11.8
Estimated Room Size (10 ft. high)	10 x 14 ft	10 x 15 ft	10 x 16 ft	10 x 16 ft	10 x 17 ft
Total Equipment Costs	\$53,875	\$59,875	\$65,575	\$77,675	\$84,575

* Includes air preparation by desiccation, ozone generation, turbine contactor, ozone destruction, and controls

** Includes monitoring of air dew point, ozone production, dissolved ozone residual in water, and ozone in ambient plant air.

Ozone Supplier B offers two types of air preparation equipment, however, and estimates are presented for each. One type operates at high pressures (80-120 psig), and the other at low pressures (8-12 psig). The high pressure air treatment units are lower in capital cost, but require more energy for their operation.

Ozone Supplier B does not normally provide a residual dissolved ozone monitor, but offers two types of monitor for ozone output from the generator. The automatic, in-line, continuous reading monitor costs $4,000; the non-automatic monitor requires wet chemistry determinations to develop data at some period of time after the sample has been taken, and costs $2,000.

Therefore, cost data presented in Table XXIII vary by the differences between costs for high and low pressure air preparation equipment, and by the costs of the two ozone generator monitors.

Cost estimates provided by Ozone Supplier C are given in Table XXIV. In contrast to the ozonation systems of Suppliers A and B, the system of Supplier C operates at sub-atmospheric pressure. The submerged turbine contactor provided by this supplier is the key to the difference in system pressure operation. When activated, the turbine creates a vacuum in the ozone generator, thereby drawing ambient air into the air preparation system, then through the ozone generator, and into the ozone contactor.

In addition, the contactor tank housing the submerged turbine is much smaller in size than the tank required for diffuser contacting. For small water supply systems treating up to 500,000 gpd with ozone, the turbine contactor tank of Ozone Supplier C is about two feet in diameter and about 30 inches high. As a result, this contactor can be incorporated into the skid-mounted ozonation system. If desired, this contactor can be installed out of doors as well.

Ozone Supplier C also provided cost estimates for water flows of 100,000, 200,000, 300,000, 400,000 and 500,000 gpd. Equipment costs for increasingly larger ozone generation volumes include costs for air preparation by means of dual tower silica gel desiccant dryers, ozone generation, ozone contacting (by submerged turbine), ozone destruction in contactor off-gases, and control systems. Costs for the four recommended ozone monitors are presented separately, and total $15,875. This cost is constant for all five systems.

It should be appreciated that if the system of Ozone Supplier C is installed in a southern U.S. location subject to high temperatures and high humidities the year round, the desiccant air preparation unit quoted in Table XXIV should be modified by addition of an air chiller unit. This will add to the equipment cost, but will reduce the operating costs. Without the chiller, the desiccant columns would have to be regenerated (thermally) much more frequently when fed high relative humidity air than when being fed low relative humidity air.

Installation Costs

Costs for installation of the ozonation equipment include labor and material costs for piping water to and from the ozone generators (if they are water-cooled), for piping ozone-containing air to the contactor chamber, for piping water to and from the contact chamber, and for piping contactor off-gases to and from the ozone destruction unit. Electrical wiring costs also must be considered in these costs. Ozonation equipment suppliers contacted advise that for production of up to about 30 lbs/day of ozone, installation costs will be roughly the same, and will average 15 to 25% of the equipment costs of the largest units estimated in Tables XXII, XXIII, and XXIV. The actual figures for the individual equipment suppliers then become:

Supplier	Cost of Equipment (500,000 gpd plant)	Installation Cost (15 to 25%)
A	$64,700	$ 9,705 - $16,175
B	$85,000	$12,750 - $21,250
C	$84,575	$12,686 - $21,143

Housing Costs

The power supply, air preparation equipment, ozone generation equipment, and turbine contacting units can be installed in existing plants relatively easily, in areas on the order of 10 x 17 feet. However, diffuser contacting units are tall (18 feet) and bulky, and normally are installed outside existing buildings (above ground) or underground inside buildings being constructed. Alternatively, a 170 sq ft Butler building can house the ozonation system, except for above-ground diffuser unit. Such a building costs about $6,000.

It should also be noted that if the small water supply system selects ozone as its primary disinfectant, then wishes to add chlorine, chlorine dioxide or chloramine for residual, equipment for addition of the desired residual-forming chemical also will be required.

Operation and Maintenance Costs

Operating costs for ozonation systems vary, and depend upon a number of factors:

- method of air preparation
- method of cooling the generator (air or water)
- if water cooled generators, the amount of refrigeration required for cooling water
- method of contacting
- dosage of ozone required
- pumping of generator coolant
- method of contactor off-gas destruction

Air Preparation

High pressure versus low pressure systems, versus sub-atmospheric pressure desiccant system with or without addition of air chiller.

Ozone Generator Cooling

Air versus water. If water, the amount of cooling required. In northern climates, water produced at the plant generally is cold enough to serve as the generator coolant the year round. In southern climates, generator cooling water must be refrigerated most, if not all, of the year.

Method of Contacting

Diffuser contactors require no added energy. Ozone/air mixtures normally are generated under a sufficient pressure to overcome the head of 16 feet of water. On the other hand, turbine diffusers require energy for their operation, but take up much less space than diffuser contactors.

Contactor Off-Gas Destruction

Atmospheric dispersion, versus thermal destruction, versus catalytic destruction. Operating costs of each of these techniques differ.

Maintenance material requirements are for periodic equipment repair and replacement of parts. Air preparation systems contain air prefilters which must be replaced frequently. Ozone generators of the tubular type normally are shut down once per year for cleaning of the tubes and other general maintenance. This can require several man-days of time, depending upon the number of ozone generators in the system. Spare parts normally consist of replacement tubes, which can be broken during cleaning, or which can deteriorate after years of operation at high voltages.

Labor requirements are for periodic cleaning of the ozone generation apparatus, annual maintenance of the contacting basins, and day-to-day operation of the generating equipment (average 0.5 hr/day).

Operating and maintenance costs for equipment of Ozone Suppliers A, B, and C for various sizes of small water supply systems up to 500,000 gpd are summarized in Table XXV. Also included are building heating costs (which are taken to be the same up to 0.5 mgd) and costs for maintenance materials and O&M labor. There are no chemicals costs related to ozone generation, except for periodic changing of desiccant in air preparation systems (usually after 10 years of use).

Electrical energy is a major component of operating costs, representing 26% to 43% of total O&M costs at small plants (0.1 mgd) increasing to 59% to 65% at the larger plants (0.1 mgd). Building energy costs (which are shown to be the same for all small size systems up to 0.5 mgd) include energy costs for heating, lighting, and ventilation. Labor costs (which are independent of the plant sizes listed - 0.1 to 0.5 mgd) account for 54% to 70% of total O&M costs at the small plants, but only 30% to 36% at the 0.5 mgd plant.

TABLE XXV

OPERATING AND MAINTENANCE COSTS FOR SMALL OZONE SYSTEMS APPLYING 3 mg/L DOSAGE

Water Flow Rate (mgd)	Electrical Energy (kWh/yr)			x $0.07/kWh =	Maintenance Material	Labor x	$10/hr =	Total Cost ($/yr)
	Building*	Process	Total			(hrs/yr)		
Supplier A								
0.18	6,570	6,661	13,231	$ 926	$120	250	$2,500	$ 3,546
0.35	6,570	12,775	19,345	$1,354	200	250	2,500	4,054
0.50	6,570	51,611	58,181	$4,073	300	250	2,500	6,873
Supplier B (High Pressure Air Preparation)								
0.10	6,570	21,900	28,470	$1,993	$120	250	2,500	$ 4,613
0.20	6,570	29,565	36,135	$2,529	120	250	2,500	5,149
0.30	6,570	34,493	41,063	$2,874	200	250	2,500	5,574
0.40	6,570	59,130	65,700	$4,599	250	250	2,500	7,349
0.50	6,570	68,985	75,555	$5,289	300	250	2,500	8,089
Supplier C								
0.10	6,570	14,783	21,353	$1,495	120	250	2,500	$ 4,115
0.20	6,570	26,645	33,215	$2,325	120	250	2,500	4,945
0.30	6,570	37,230	43,800	$3,066	200	250	2,500	5,766
0.40	6,570	44,895	51,465	$3,603	250	250	2,500	6,353
0.50	6,570	53,838	60,408	$4,229	300	250	2,500	7,029

* Estimated from data of Reference 39

Summary Statement Regarding Costs For Ozonation Systems

Because of the many differences in methods of air pretreatment, ozone contacting, contactor off-gas destruction, monitoring, and other operational parameters, equipment costs given above should not be considered as more than general guidelines. No attempt should be made to update these costs in the future by applying Engineering News Record Indices. Instead, at the time ozone is being considered by the small water supply system, vendor quotes should be obtained at that time.

However, it also should be noted that vendor quotes obtained for estimating purposes are likely to be higher than firm bids made to specifications. This is because the market for ozonation systems currently is quite competitive, and suppliers usually bid their best prices when responding to clear specifications.

COSTS FOR DISINFECTION WITH ULTRAVIOLET RADIATION

Construction Costs

Table XXVI summarizes costs developed in 1978 (39). The major change which has occurred through 1982 is that the costs for UV generating units (manufactured equipment) in the size ranges listed are about 15% higher. Data presented in Table XXVI are for single and multiple UV lamp disinfecting units ranging in capacity of water throughput from 14,400 gpm to 1,123,200 gpm.

All UV generating units are quite compact, the 1,123,400 gpm unit occupying an area of less than 24 ft^2. Costs listed in Table XXVI include equipment costs of the UV units, and the related costs of piping, electrical equipment, equipment installation, and a building to house the equipment.

As was the case with disinfection by ozone, if the water system wishes to disinfect with UV, then follow with a residual of chlorine, chlorine dioxide, or chloramine, additional equipment will be required to provide the residual disinfectant selected.

Operating and Maintenance Costs

These are shown in Table XXVII for the same size plants as in Table XXVI. Process energy is required for the mercury lamps operating inside of the UV generating units. Continuous 24-hr/day operation is assumed, with only occasional shutdown to clean cells and replace ultraviolet lamps which have become weakened by lengthy use. Building energy requirements are for heating, lighting, and ventilation.

Maintenance materials are related to the replacement cost of the ultraviolet lamps, which usually are replaced after operating continuously for about 2,000 hours (about eight months).

TABLE XXVI

CONSTRUCTION COSTS FOR ULTRAVIOLET LIGHT DISINFECTION

Cost Category	Plant Capacity (gpd) 14,400	28,800	187,200	374,400	748,800	1,123,200
Excavation and Sitework*	$ 60	$ 60	$ 60	$ 60	$ 80	$ 110
Manufactured Equipment	800	1,125	4,485	8,685	17,365	26,050
Concrete*	250	250	250	250	280	300
Labor*	110	170	250	300	400	500
Pipe and Valves*	60	150	350	450	750	1,000
Electrical and Instrumentation*	430	430	430	430	480	480
Housing*	1,500	1,500	1,500	1,500	1,800	2,000
SUBTOTAL	3,210	3,885	7,225	11,675	21,155	30,440
Miscellaneous and Contingency*	470	560	1,010	1,580	2,830	4,060
TOTAL	$3,680	$4,445	$8,335	$13,255	$24,085	$34,500

* Data from Reference 39

Labor requirements are related to occasional cleaning of the quartz sleeves which surround the mercury vapor lamps, and periodic replacement of the weak UV bulbs.

It is noteworthy that replacement bulb costs at the smallest plant (14,400 gpm) are only about 9% of the total O&M costs, whereas at the largest plant size (1,123,200 gpm) replacement bulb costs are about 48% of the total O&M costs. This reflects the fact that the larger UV generating units contain a greater number of UV bulbs per unit volume of water treated.

No chemical costs are associated with the use of UV radiation per se; however, following UV with a residual disinfectant (chlorine, chlorine dioxide, or chloramine) will add costs for these chemicals. The use of UV radiation for primary disinfection will lower the amounts of chemicals subsequently used for maintaining a disinfectant residual in the product water.

TABLE XXVII

OPERATION AND MAINTENANCE SUMMARY FOR ULTRAVIOLET LIGHT DISINFECTION

Plant Flow	Energy (kWh/yr*						Maintenance	Labor				Total Cost
Rate (gpm)	Building	Process	Total	x	$0.07/kWh	=	Matl.*($/yr)	(hr/yr)	x	$10/hr	=	($/yr)
14,400	10,260	440	10,700		$ 749		$ 100	24		$240		$ 1,089
28,800	10,260	800	11,140		780		140	24		240		1,160
187,200	10,260	5,260	15,520		1,086		600	24		240		1,926
374,400	10,260	10,510	20,770		1,454		1,120	30		300		2,874
748,800	12,310	21,020	33,330		2,333		2,250	36		360		4,943
1,123,200	13,340	31,540	44,880		3,142		3,300	42		420		6,862

* Data from Reference 39

APPENDIX B

HOW TO TAKE BACTERIOLOGICAL SAMPLES

Routine and special bacteriological samples must be taken in accordance with established procedures to prevent accidental contamination, and analyzed by an EPA- or state-certified laboratory. Usually the lab will provide specially prepared sampling containers, properly sterilized and containing sodium thiosulfate to destroy any remaining chlorine. If water system personnel prepare containers, follow the procedures given in Reference 5.

The following steps should be observed in coliform sampling:

1) use only containers which are provided by the bacteriological laboratory and which have been prepared for coliform sampling. Follow all instructions for sample container handling and storage.

   THE CONTAINERS ARE STERILE. DO NOT OPEN THEM BEFORE USE AND DO NOT RINSE THEM.

2) take samples at the consumer's faucet, but avoid:

   faucets with aerators (unless removed) or swivel spouts;

   taps inside homes served by home water treatment units such as water softeners;

   locations where the water enters separate storage tanks; and

   leaking faucets that permit water to run over the outside of the faucet.

3) always allow the water to flow moderately from a faucet two or three minutes before taking the sample;

4) hold the sample container at the base keeping hands away from the container neck. Be sure the inside of the container cap is protected and does not touch anything.

5) without adjusting the flow, fill the sample container, leaving about 20% air space at the top. Replace the cap immediately. If the sample is collected incorrectly, take another sample container -- do not reuse the original bottle:

6) take a second sample and measure the concentration of the disinfectant and record relevant information (date, time, concentration, place, sampler, etc.);

7) package the bacteriological sample for delivery to the lab. Record all pertinent field information on a form and on the sample container label;

8) samples must be cool during shipment to the lab. Use insulated boxes for shipping containers if needed, or refrigerate during transit.

   SHIP IMMEDIATELY VIA EXPRESS TRANSPORT. DO NOT ALLOW MORE THAN 30 HOURS BETWEEN SAMPLING AND TEST TIMES.

Be sure the laboratory can process the samples immediately upon receipt.

MONTHLY BACTERIOLOGICAL SUMMARY

Multiple-Tube Fermentation Method

____
Water System ID

____
Water System

Number of Samples Required ______________________

SAMPLING INFORMATION							LAB ANALYSIS INFORMATION					
Date	Time	Location	Sampled By	Type			Sample ID #	Date	Routine Samples			Check Samples
				Routine	Check	Checking Routine Sample of (date)			No. of Tubes	No. of Positive Tubes	No. of Samples with 3 or more Positive Tubes	No. of Positive Tubes
1	2	3	4	5	6	7	8	9	10	11	12	13

☐ TOTAL Number of Routine Samples for the Month

☐ TOTAL Number of Tubes Used in Monthly Tests

☐ TOTAL Number of Positive Tubes

☐ TOTAL Number of Samples with 3 or more Positive Tubes

MONTHLY CALCULATIONS

I. CALCULATE THE MONTHLY PERCENTAGE —

$$\text{\% of Tubes Positive} = \frac{\text{TOTAL No. of Positive Tubes}}{\text{TOTAL No. of Tubes Used in Monthly Tests}}$$

II. DETERMINE THE NUMBER OF TIMES 3 OR MORE PORTIONS WERE POSITIVE —

For Systems Taking Fewer than 20 Samples Per Month:
Use the total box, "TOTAL Number of Samples with 3 or more Positive Tubes", to determine compliance with the MCL.

For Systems Taking 20 or More Samples Per Month:

$$\text{\% of Samples with 3 or More Positive Tubes} = \frac{\text{TOTAL No. of Samples With 3 or More Positive Tubes}}{\text{TOTAL No. of Routine Samples for the Month}}$$

____
Person responsible for analysis

MONTHLY BACTERIOLOGICAL SUMMARY

Membrane Filter

____
Water System ID

____
Water System

Number of Samples Required _______________

SAMPLING INFORMATION							LAB ANALYSIS INFORMATION				
Date	Time	Location	Sampled By	Type			Sample ID#	Date	Routine Samples		Check Samples
				Routine	Check	Checking Routine Sample of (date)			Colonies/ 100 ml	Samples Exceeding 4/100 ml	Colonies/ 100 ml
1	2	3	4	5	6	7	8	9	10	11	12

☐ TOTAL Number of Routine Samples for the Month

☐ TOTAL Number of Coliform Colonies For the Month

☐ TOTAL Number of Routine Samples Exceeding 4/100 ml

MONTHLY CALCULATIONS

I. CALCULATE THE MONTHLY AVERAGE VALUE —

$$\text{Average Coliform Density for the Month} = \frac{\text{Total No. of Coliform Colonies}}{\text{Total No. of Routine Samples}}$$

II. DETERMINE THE NUMBER OF TIMES 4 COLONIES/100 ml WAS EXCEEDED —

For Systems Taking Fewer Than 20 Samples Per Month:

Use the total box — "TOTAL Number of Routine Samples Exceeding 4/100 ml"

For Systems Taking 20 or More Samples Per Month:

$$\text{\% of Samples Exceeding 4/100 ml} = \frac{\text{TOTAL No. of Samples Exceeding 4/100 ml}}{\text{TOTAL No. of Routine Samples Taken}}$$

____
Person responsible for analysis

APPENDIX C

DISINFECTANT RESIDUAL SAMPLING

Chlorine is the disinfectant in most common use in the U.S. for sanitizing drinking water. Its most active form is as the 'free residual', which is stable only in the absence of agitation, sunlight, and certain inorganic and organic materials with which it can react.

Reactions of free residual chlorine with chlorine-demanding substances continue over long periods of time. Therefore, the sample taken for disinfectant analysis must be analyzed immediately. Specially prepared sampling containers, properly cleansed, sterilized, and not containing sodium thiosulfate should be employed. In general, the same sampling precautions described in Appendix B for taking coliform samples should be observed, but in addition:

1) draw the sample gently, avoiding agitation;

2) analyze immediately in the shade or subdued light. Do not store the sample;

3) do not use a bacteriological sampling container which may contain a chemical to counteract or destroy the disinfecting agent.

☆U.S. GPO: 1983-381-082/425